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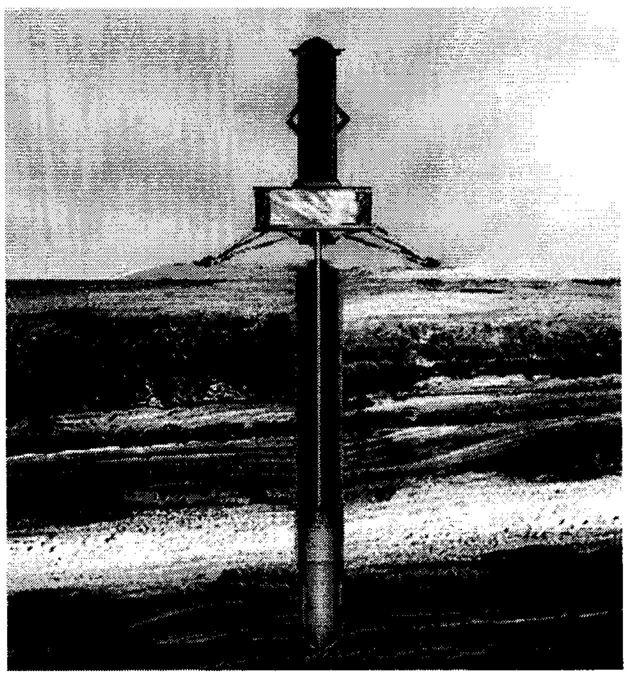
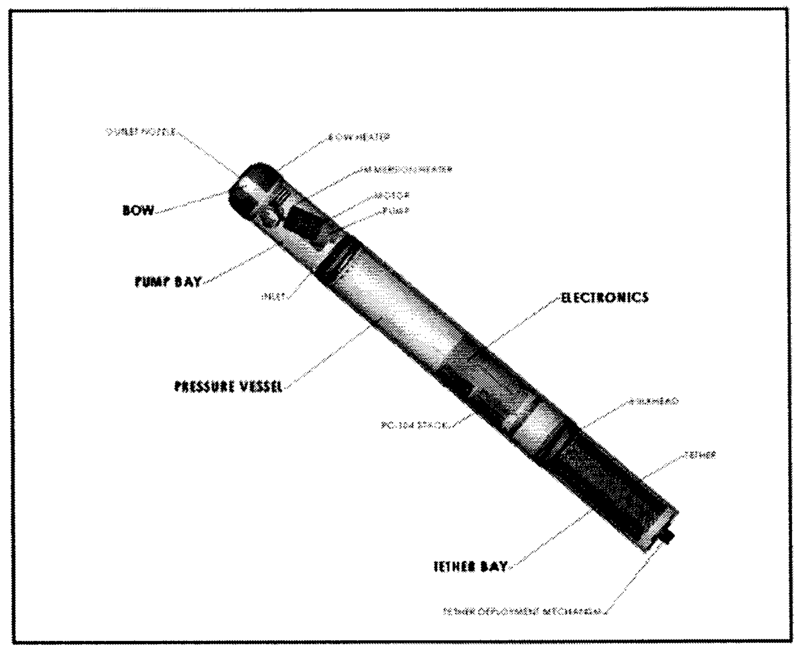
Cryobot: Subsurface Exploration of Earth, Mars, and Europa

MARS CRYOSCOUT
EXPLORING THE POLE

What is a Cryobot?





Science Goals and Objectives

APPROACH: Cryobots explore climate history by:

- Examination of undisturbed ice adjacent to a "Cryobot" thermal probe
- Analysis of meltwater produced in the descent

THEME: Climate and atmospheric history: The present and the link to the past

OBJECTIVES:

- Determine the recent climate history of Mars.
- Study structure, stratigraphy, and sedimentology of the polar cap.
- Characterize present-day polar surface/atmosphere interactions
- Constrain the search for evidence of martian life through chemical and physical assessment of the meltwater.

NASA'S Science Objectives

- **Observe the formation of planetary systems and characterize their properties**
- **Search for worlds that could harbor life**
- **Learn why the planets in our Solar System are so different from each other**
- **Investigate the origin and early evolution of life on Earth, and explore the limits of life in terrestrial environments that might provide analogues for conditions on other worlds**
- **Determine the general principles governing the organization of matter into living systems and the conditions required for the emergence and maintenance of life**
- **Chart the distribution of life sustaining environments within our solar system, and search for evidence of past and present life**
- **Identify plausible signatures of life on other worlds**
- **Understand forces and processes, such as impacts, that affect habitability of Earth**
- **Find extraterrestrial resources and assess the suitability of Solar System locales for future human exploration**

- **Evolution of Planetary Surface**
- **History of climate**
- **Search for life**

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Life, Climate, and Water

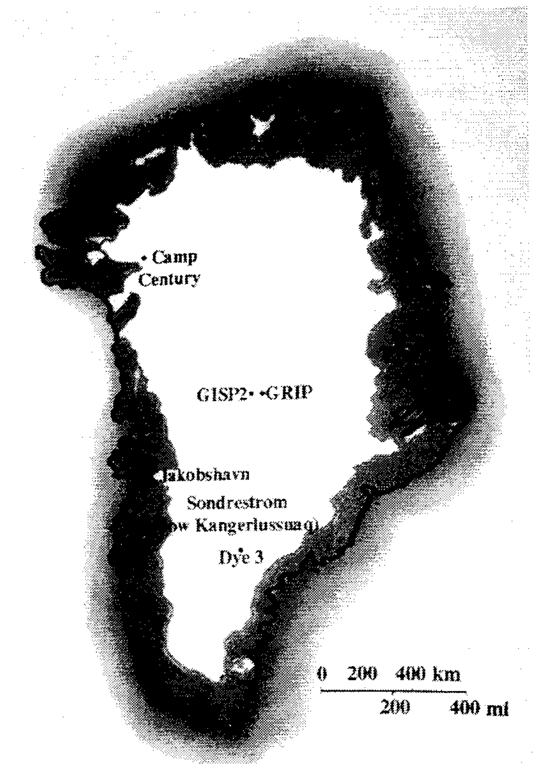
- The range of forms life may occur in remains unknown:
  - Temperature extremes
    - Life found in high temperature regimes: Black smokers [*Corliss*, 1990]
    - The universal phylogenetic tree of 16s ribosomal RNA of Batceria, Eubacteria, and Eucarya may be centered on hyperthermophiles formed during period following terrestrial accretion [*Farmer*, 1998]
    - Low termperature origin also plausible - may have been wiped out by high temperature events such as late giant impacts [*Forterre*, 1996]
    - In Antartic ice bacterial life exists around food sources such as dust grains
    - Cold requires more energy [*Mazur et al.*, 1978]
  - Not fully known range of sizes, e.g. ALH84001 [*McKay et al.*, 1996]

- What we do know:
  - Extant life associated with water
  - Fossil life likely to form in association with past water
  - Climate critical to the question of water environment for life

Terrestrial Background

- Earth, Mars, and Europa are targets of study:
  - Water rich in the past/present
  - Likely had habitable climates

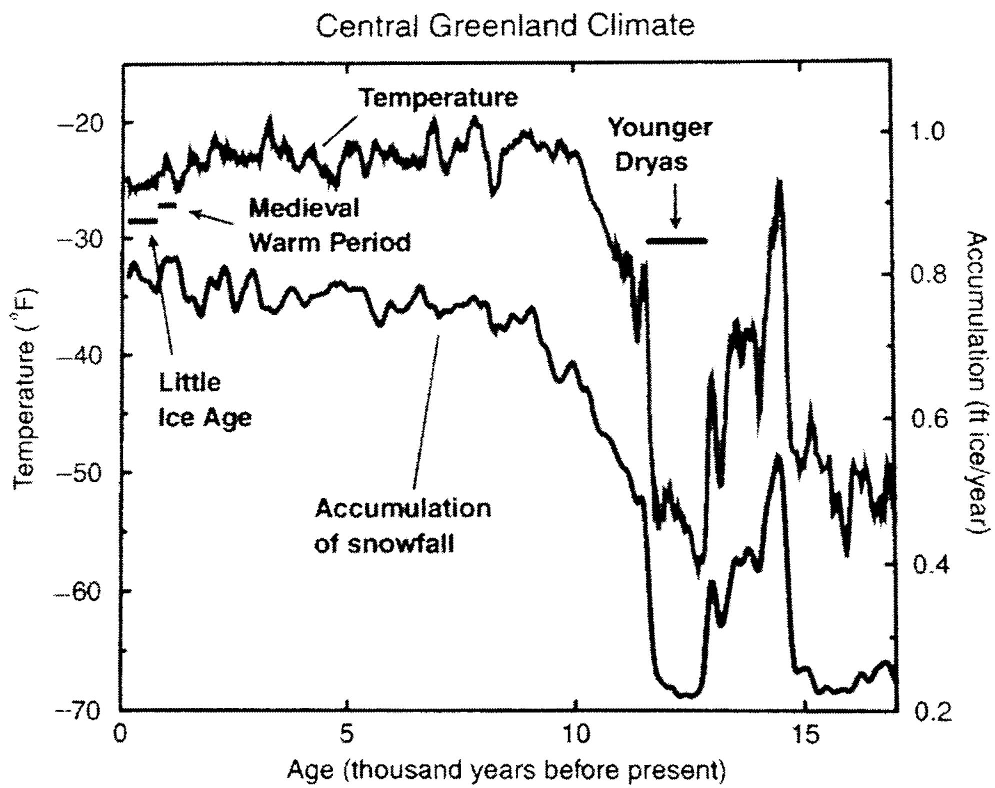
- Use the Earth to understand climate
  - Ice core studies of temperature
  - Age dating
    - $\delta^{16}O/\delta^{18}O$
    - Conductivity
    - pH
    - Visible layering
    - Dust layering



Adapted from *Alley*, 2000

Terrestrial Background

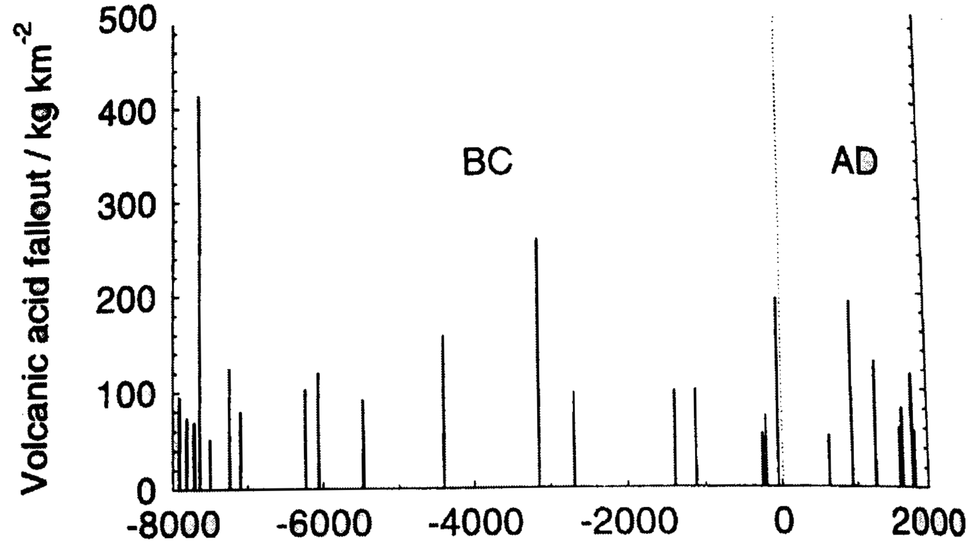
- Climate important to life
  - Medieval culture flourished during warming
  - Vikings chased out of Greenland by cooling
  - Ancient swings much larger
  - Controversy about older temperature swings



Cuffey and Clow, 1997

Terrestrial Background

- Layers placed down by volcanic eruptions dated to before recorded history [*Hammer*, 1980]



Adapted from *Wolff*, 2000

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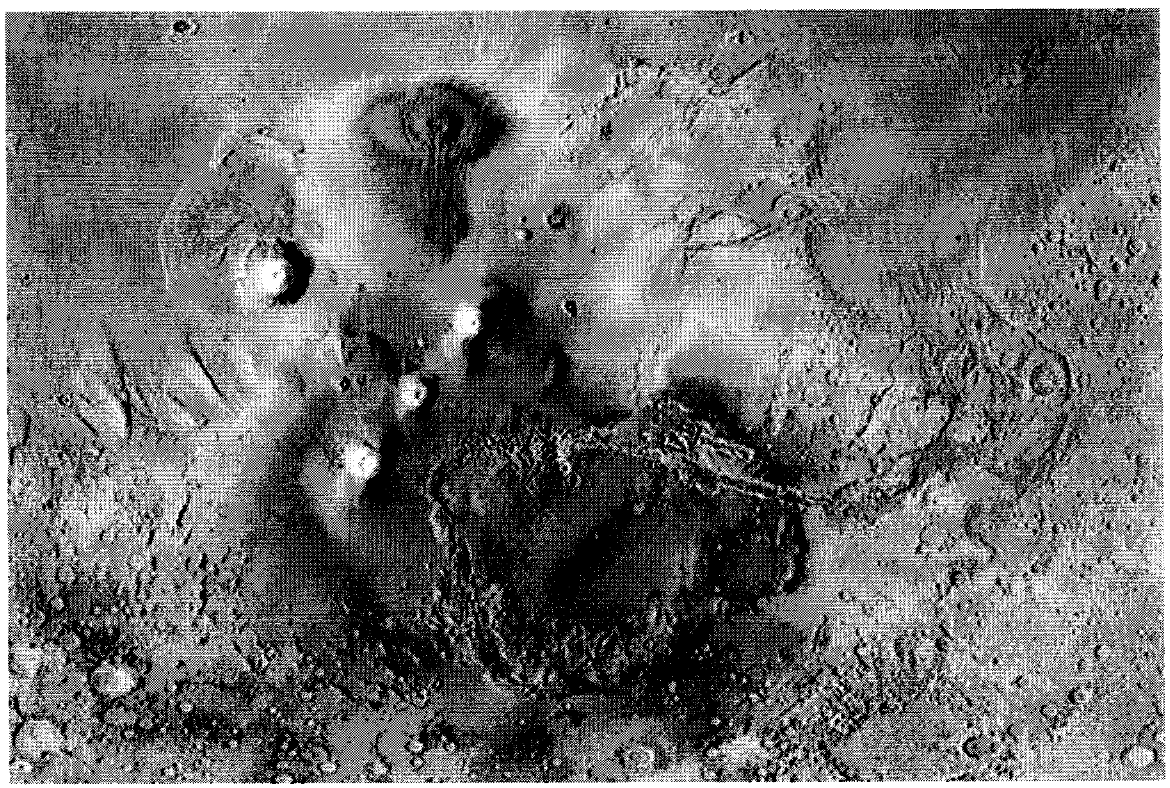
MARS CRYOSCOUT
EXPLORING THE POLE

Mars

- Mars today has little or no liquid water on the surface
- Past Mars looks entirely different
  - Extensive channels
  - Extraordinarily smooth northern plains
  - Wave eroded terraces surrounding northern lowlands



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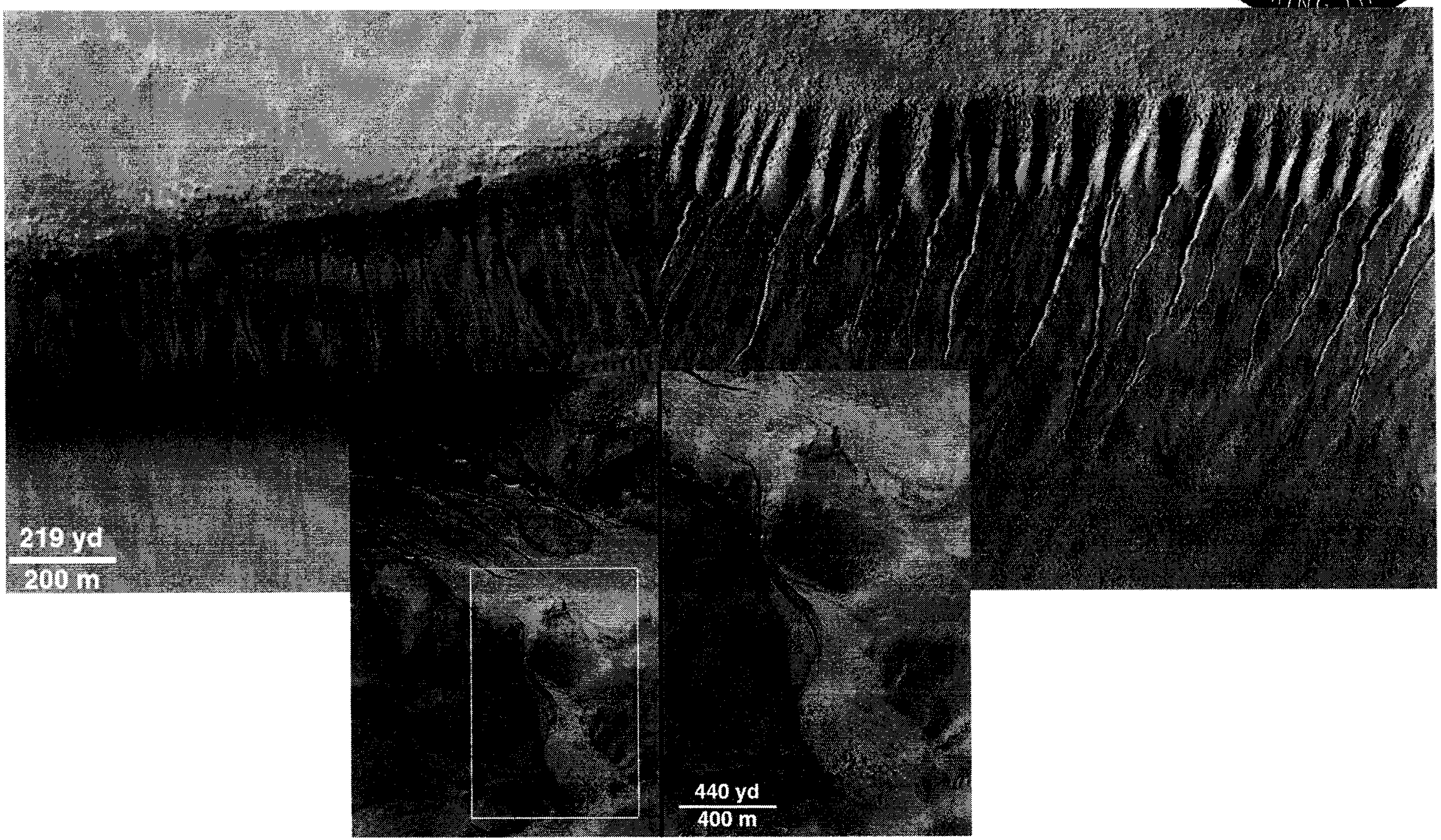
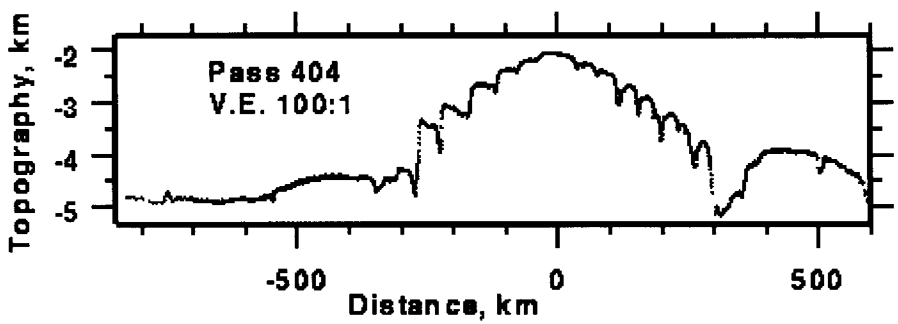
Mars

- Water today may exist at seeps, or may be freezing phenomena

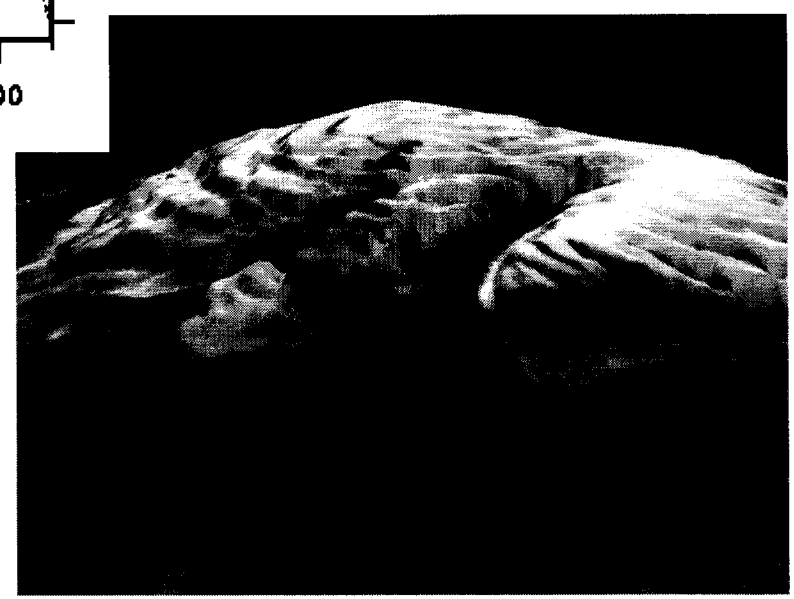


Mars Northern Pole

- Most likely place to find water and understand climate for Mars is northern polar ice cap



- Temperature consistent with H_2O
- H_2O vapor during summer



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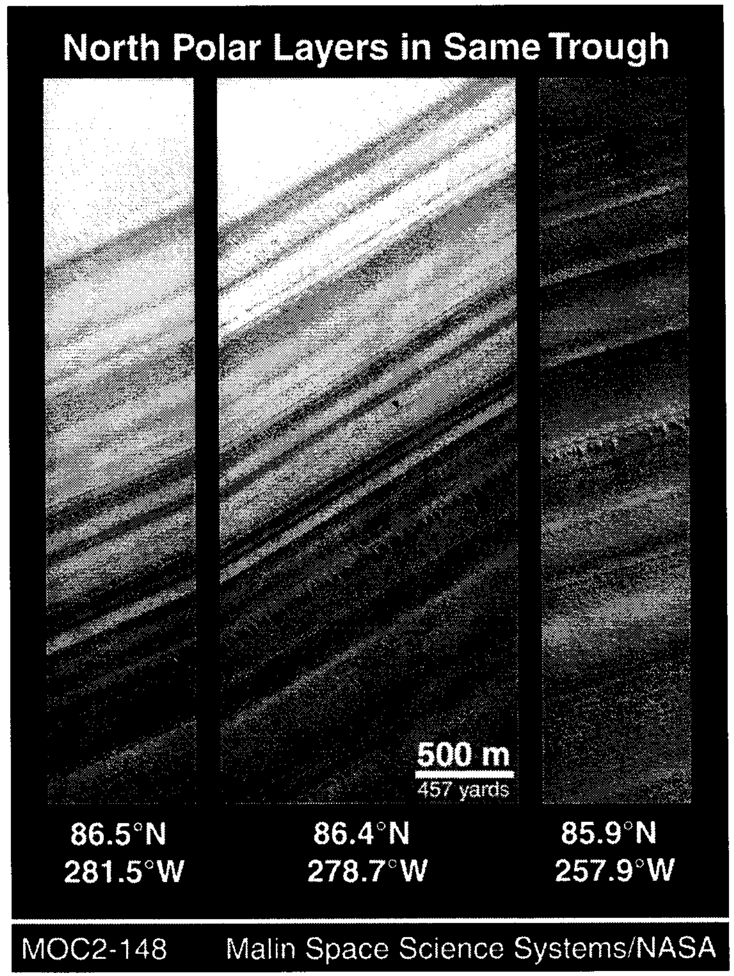
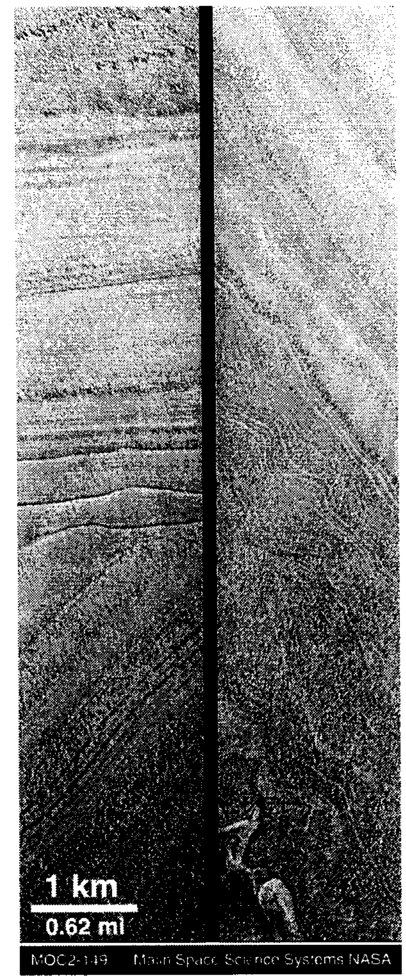
Mars Northern Pole

- Polar cap has similarities to terrestrial caps: Layering => Climate history
- Layers dusty
- Areally extensive
- Dust may provide biology
  - Food
  - Transport
  - May be an impediment
- Little known about
  - Dust content
  - Deposition history
  - Chemical constituents





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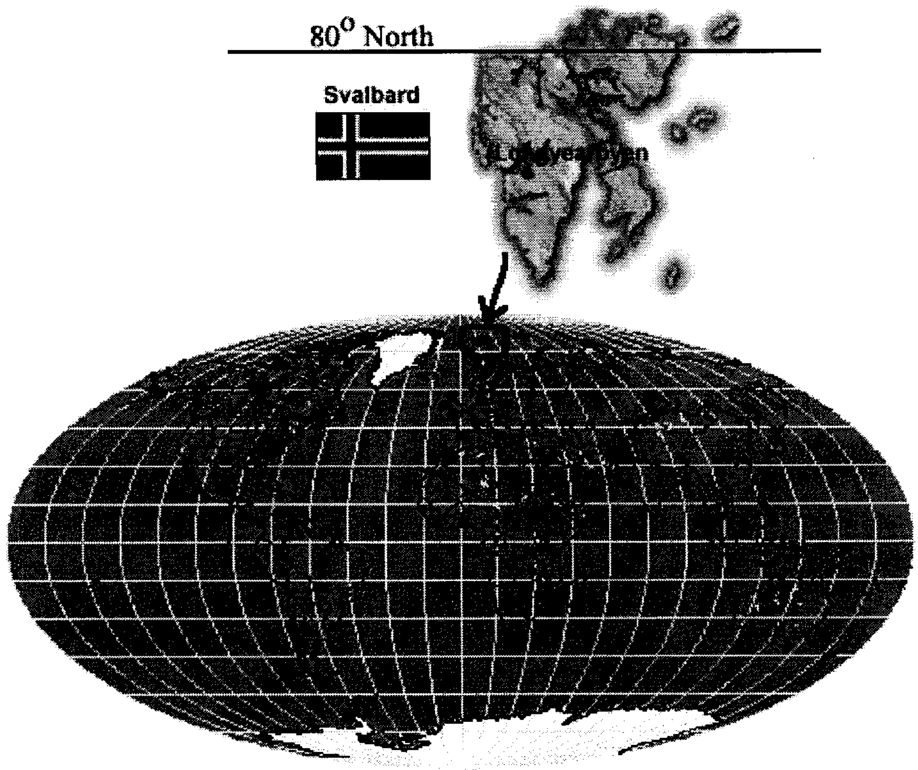
Data Analysis Approach

- Primary task is to assign chronology to strata by assessment of optical, isotopic, and chemical characteristics. This will be baseline for further analysis.
- Prepare for presentation plots of density, isotopic ratio, chemistry, thermal diffusivity, and other characteristics vs. time/depth.
- Verify cryobot descent rate and depth from GPR. Place sampled volume in context of coarse vertical profile of entire cap.
- Infer history of polar cap mass balance and surface/atmosphere interactions
- Analyze results in terms of past climate for publication.
- Parallel effort on describing present-day climate and topography.
- Will prepare sequential images as winter accumulation of CO_2 frost sublimates.

Field Test of the Cryobot in Svalbard



Dr. F. Scott Anderson

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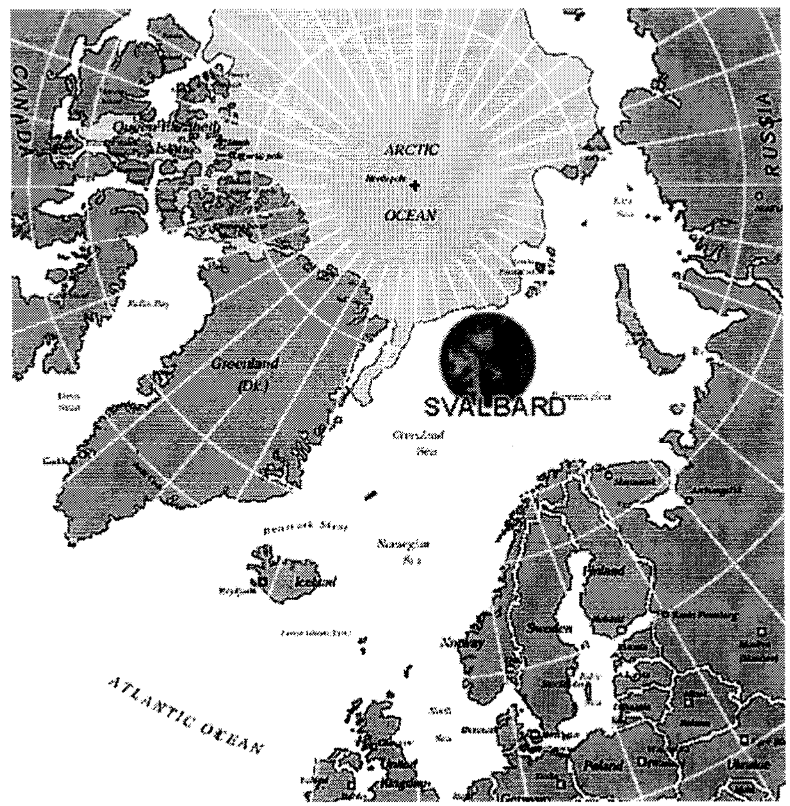
Svalbard

- **Schedule moved up due to:**
  - **Cryoscout opportunity**
  - **Threatened lack of funding in FY2002**
- **Ideal for engineering test**
  - **Integrated electronics**
  - **Thermodynamics of melt**
  - **Real world conditions**
  - **30-100 m melt**
- **Science piggybacked on test**
  - **Camera**
  - **Chemistry sensor**
  - **Ice core**
  - **Not main goal**
- **Why Svalbard?**
  - **100 meter glacial ice**
  - **600 meter ice sheet**
  - **"Temperate" Conditions**
  - **Logistical support from the Norwegian Polar Institute**
  - **Rapid field planning capability**
  - **Easy access via standard air carriers**

MARS CRYOSCOUT
EXPLORING THE POLE

Map of Svalbard



Ride to the Glacier

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Bringing in the Operations Hut

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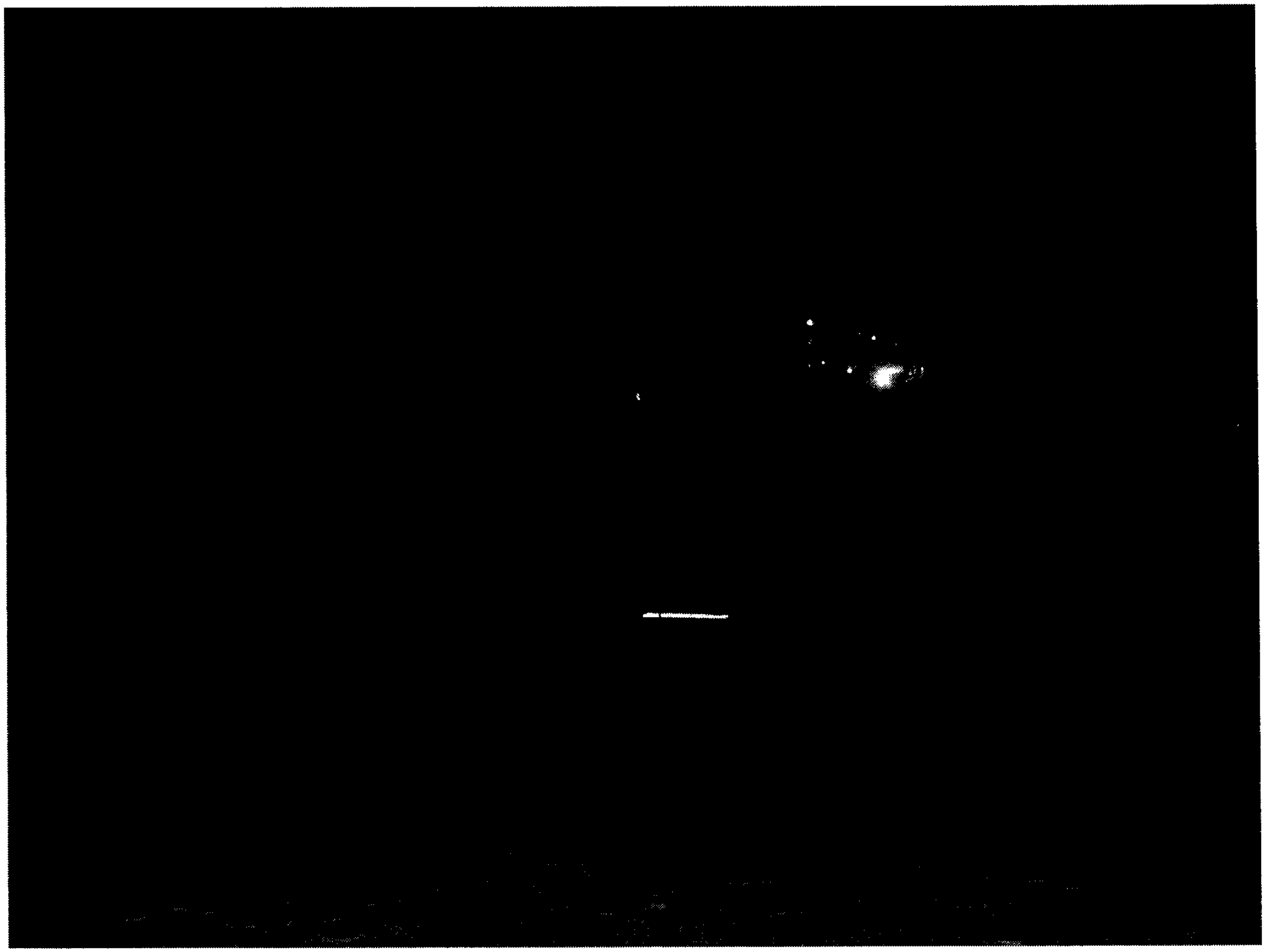
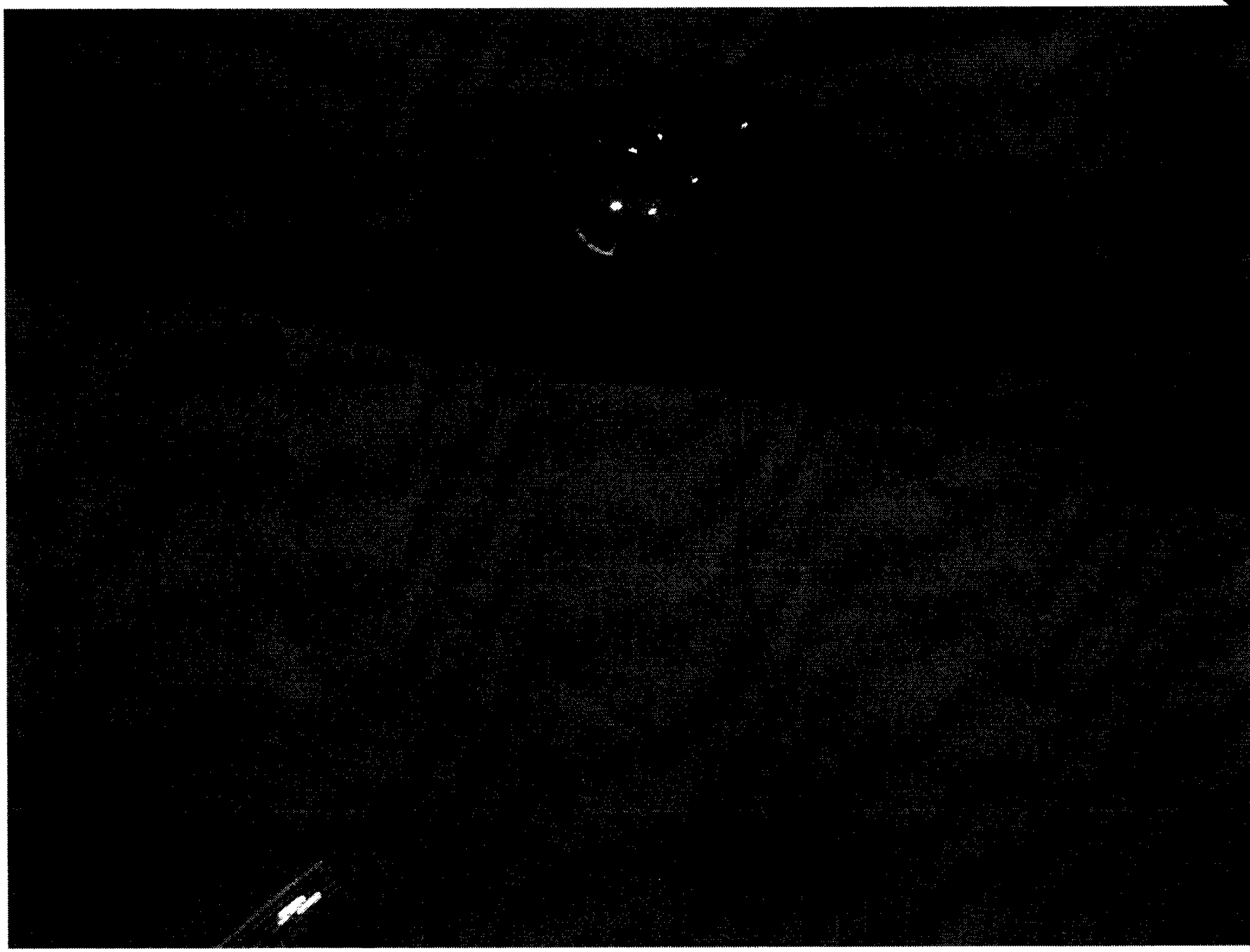
EXPLORING THE POLE



Other Equipment



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Preparing Operations/Camping Area on Ice

Back in Town

- Oct 20:
  - Inspected cryobot
  - Noted loss of pump/motor can fluid
  - Chemistry sensor has communication problems
  - Chemistry sensor fix will wait until after initial 30 m melt

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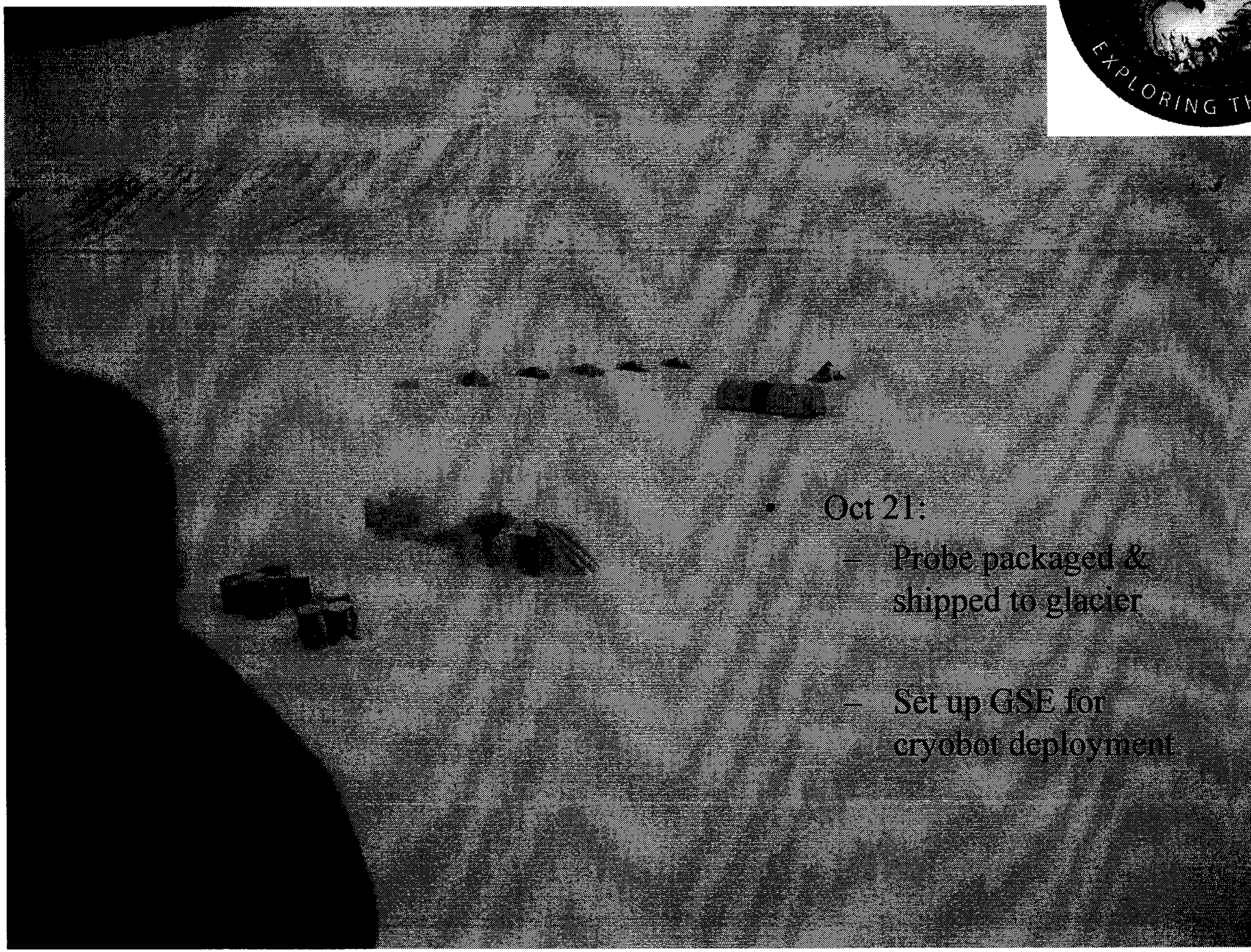
MARS CRYOSCOUT
EXPLORING THE POLE

Team Arrives with Cryobot on Glacier



- Oct 21:
  - Probe packaged & shipped to glacier
  - Set up GSE for cryobot deployment

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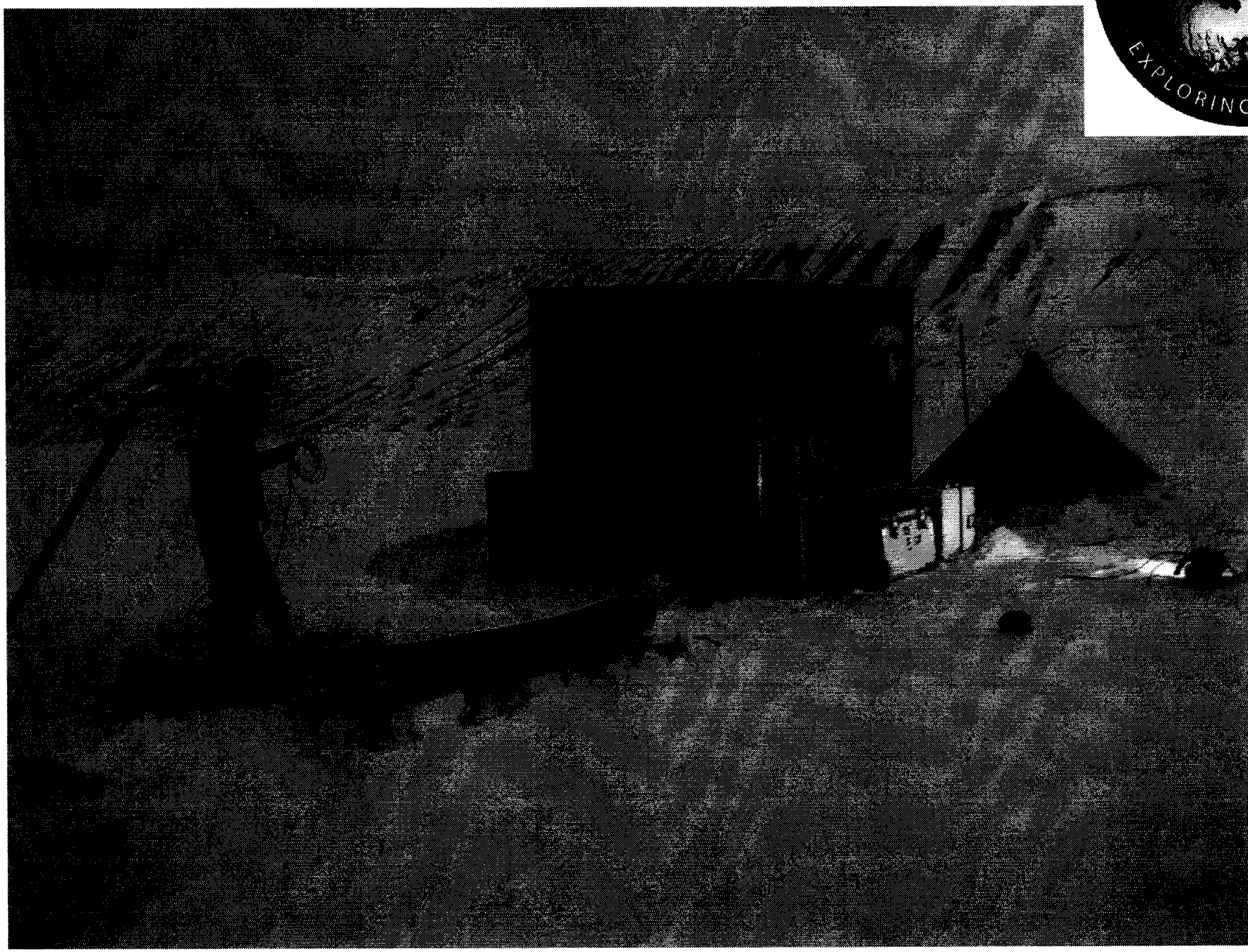
The Setup



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MARS CRYOSCOUT
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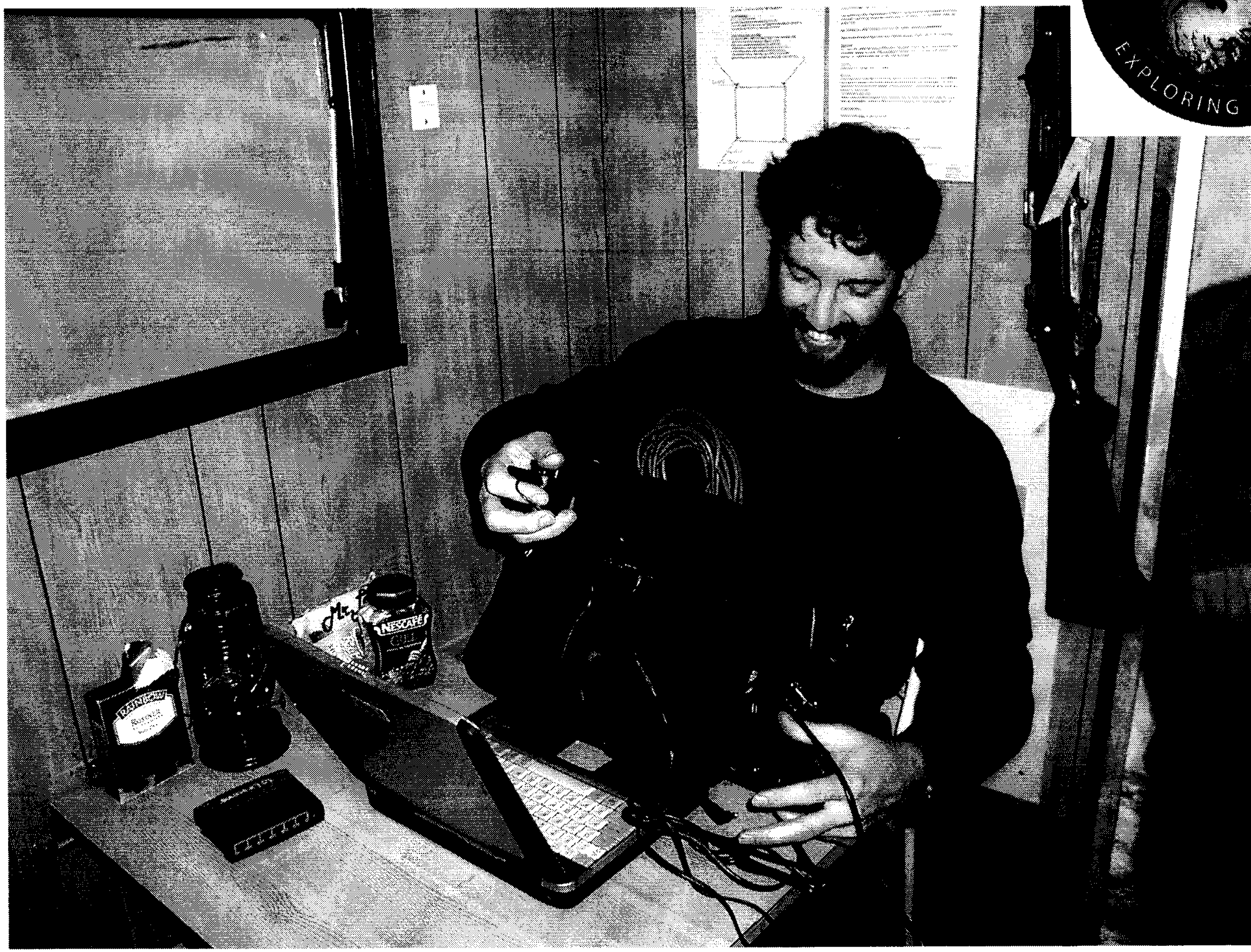
GSE



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Oct 22: 2AM Cryobot Deployed

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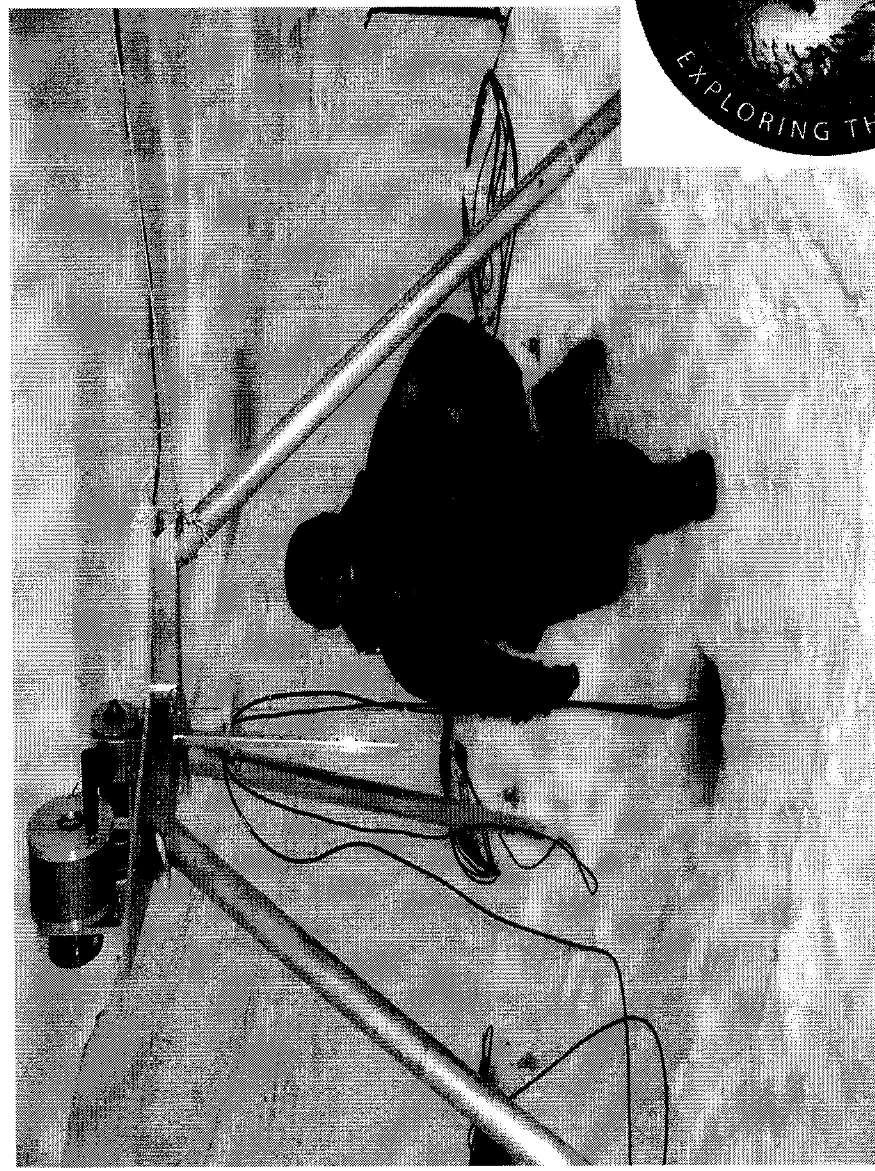
MARS CRYOSCOUT
EXPLORING THE POLE

Oct 22: 10 AM   Active Melt Initiation

- Passive (550W) & active (400W) melting.
- Descent rate 55cm/hr.
- Water level sensor signals a full resevoir.
- Active melting began when cryobot had descended ~40cm.



Active Melt

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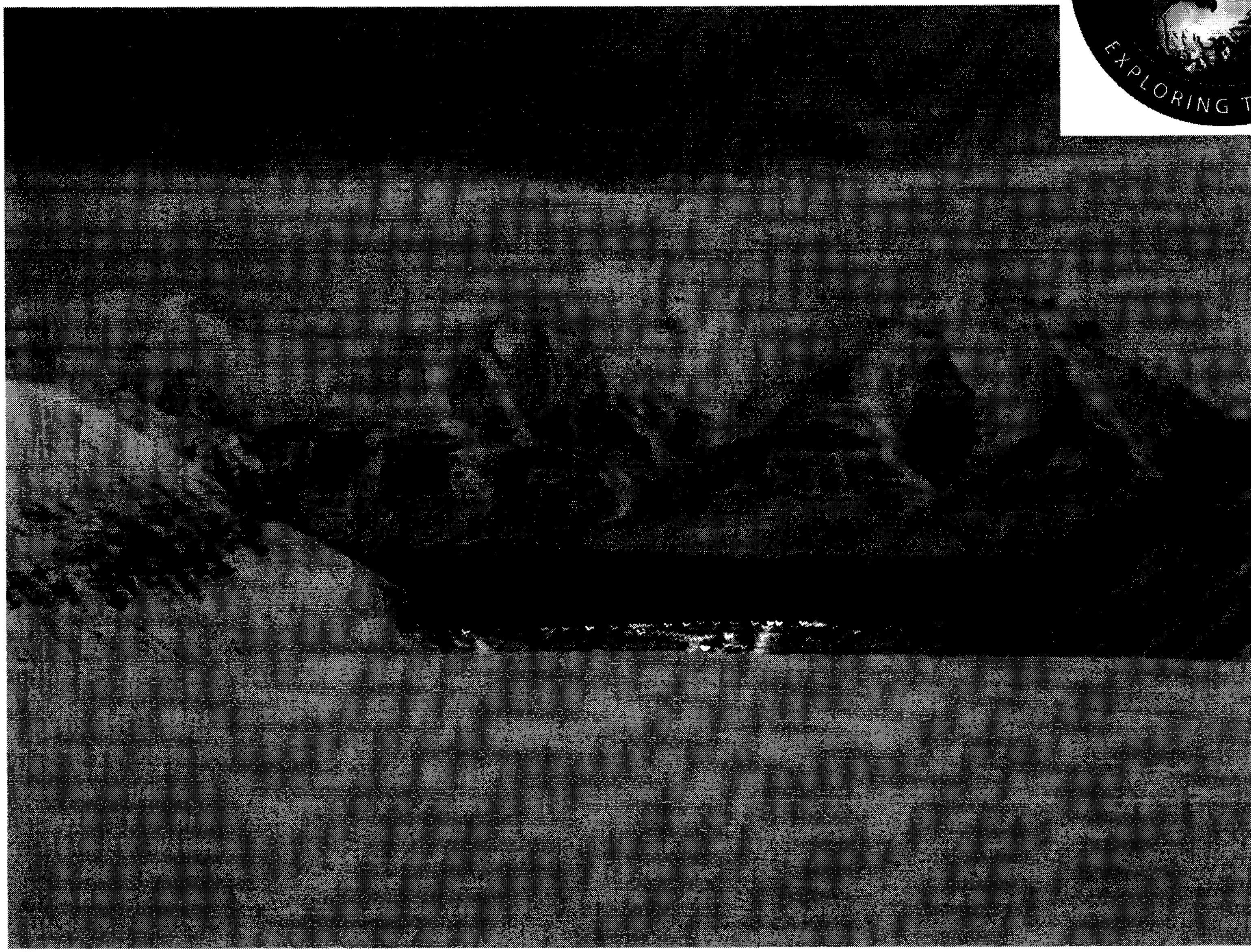
"It's like watching ice melt…"



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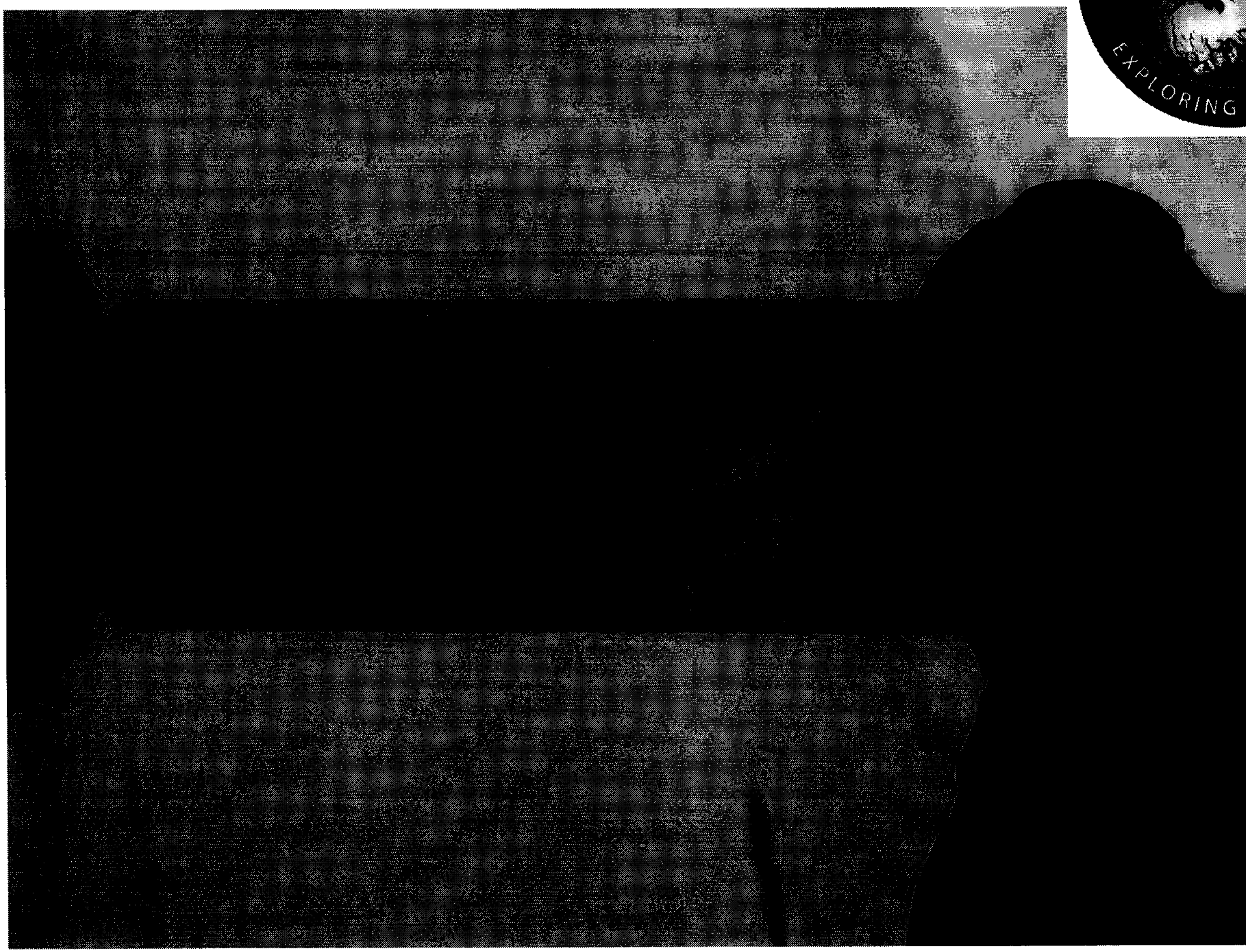
Ice Coring

Dust Core



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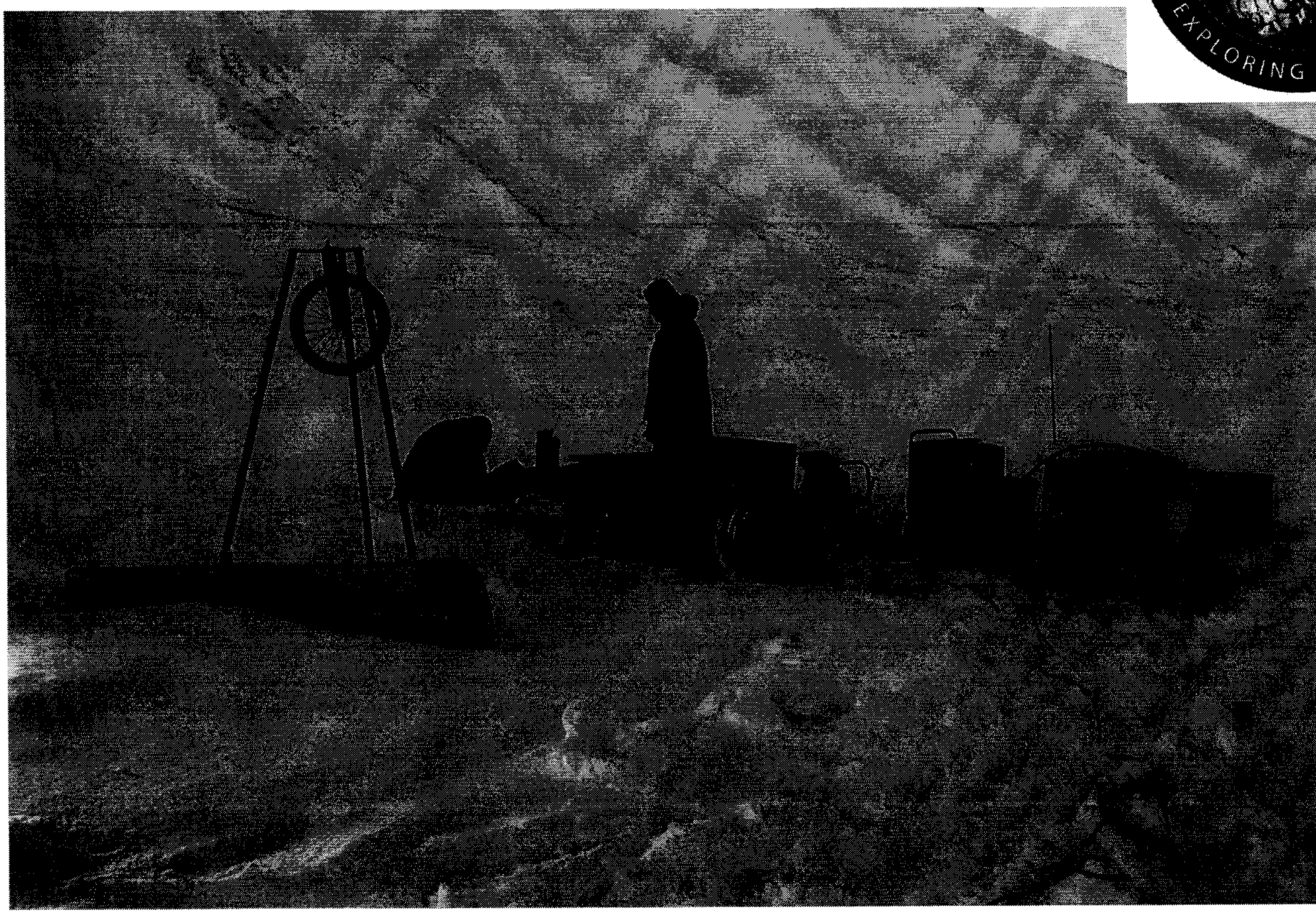
Removed cryobot from glacier using hot water drill



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MARS CRYOSCOUT EXPLORING THE POLE

Cryobot Recovery

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Conclusions

- Engineering test a resounding success
  - Never before has an integrated active/passive probe system ever been demonstrated
  - Went ~5x further than previous test
  - Didn't meet distance goals
    - However, these were simply made up, not chosen based on experience
    - We expect it to be no problem to go further
  - All engineering issues are readily resolvable
    - Cold hardened parts
    - Better pump motor
    - Better leak protection

- Science effort beginning
  - Small effort to get chemistry sensor and camera working in ice test bed
  - When ice cores arrive will be examined for dust loading and bio-signatures
  - New instruments being designed for Scout/Terrestrial experiements

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Cryobot Instruments

- Optical system characteristics (JPL)
  - Imager w/ filter wheel & line sources; point spectrometer; scatterometer
  - Heritage: Commercial, common elements with many flight instruments
  - Key performance characteristics in adjacent box and following page
  - Earth field trials designed to reduce risk
- Electrochemistry (Kounaves/Tufts & Buehler/JPL)
  - Flow-through system w/ pH, redox, voltammetry, & ion selective electrodes
  - MECA heritage
  - Extensive prototyping underway
- $^{18}O/^{16}O$ TDL spectrometer (Webster, JPL)
  - Sensitivity to better than part per mil
  - Heritage: MVACS

Optical System Measurement Objectives

- Dust density (optical depth in 3 bands), Dust size (reflectance vs. angle), Stratigraphy & embedded objects, Mineralogy

Configuration

- Maximum resources: 1 kg, 1L, 50W, 1 Gbyte
- Side looking (fiber couple to pump bay for CE)
- 1 cm working distance, 0.1 mm depth-of-focus
- Working temperature 0-10°C, survival to -110°C
- Ability to inject stains for organics, pH, etc. (fluorescamine absorbs ~300-400, emits ~500)

Imaging

- Low & high resolution images
- RGB & polarizing filters
- 0.1 mm vertical resolution

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Instrumented Tether

- **Fiber Thermometer (J. Johnson, CRREL: SPEC, Inc., vendor).**
  - **Commercial heritage, intrinsically rugged**
  - **<1 meter, 0.1K resolution over 200m**
  - **~90 secs per reading**
  - **Met with vendor during study and identified minor modifications for Mars application. Proposed for Earth Science field study.**

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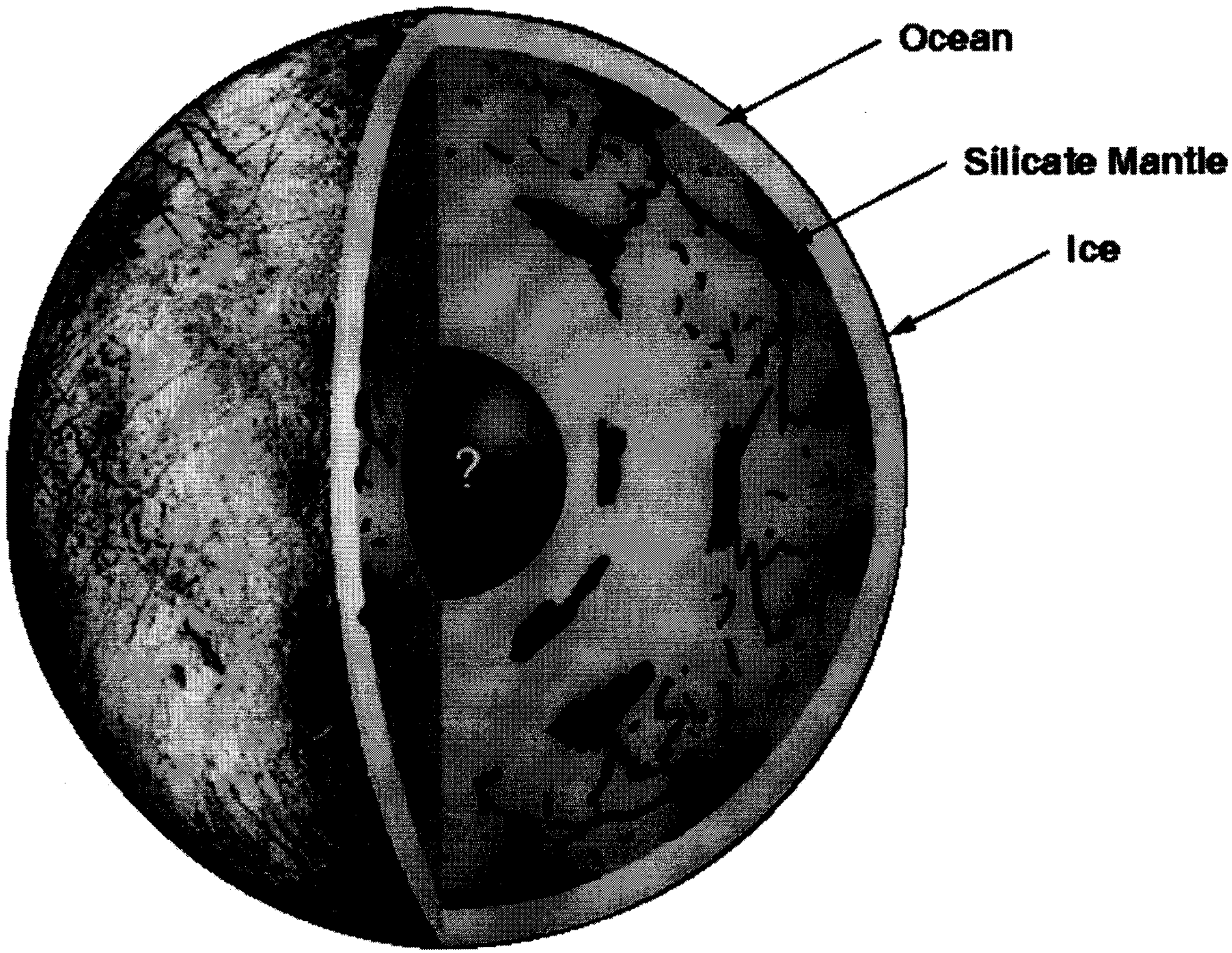
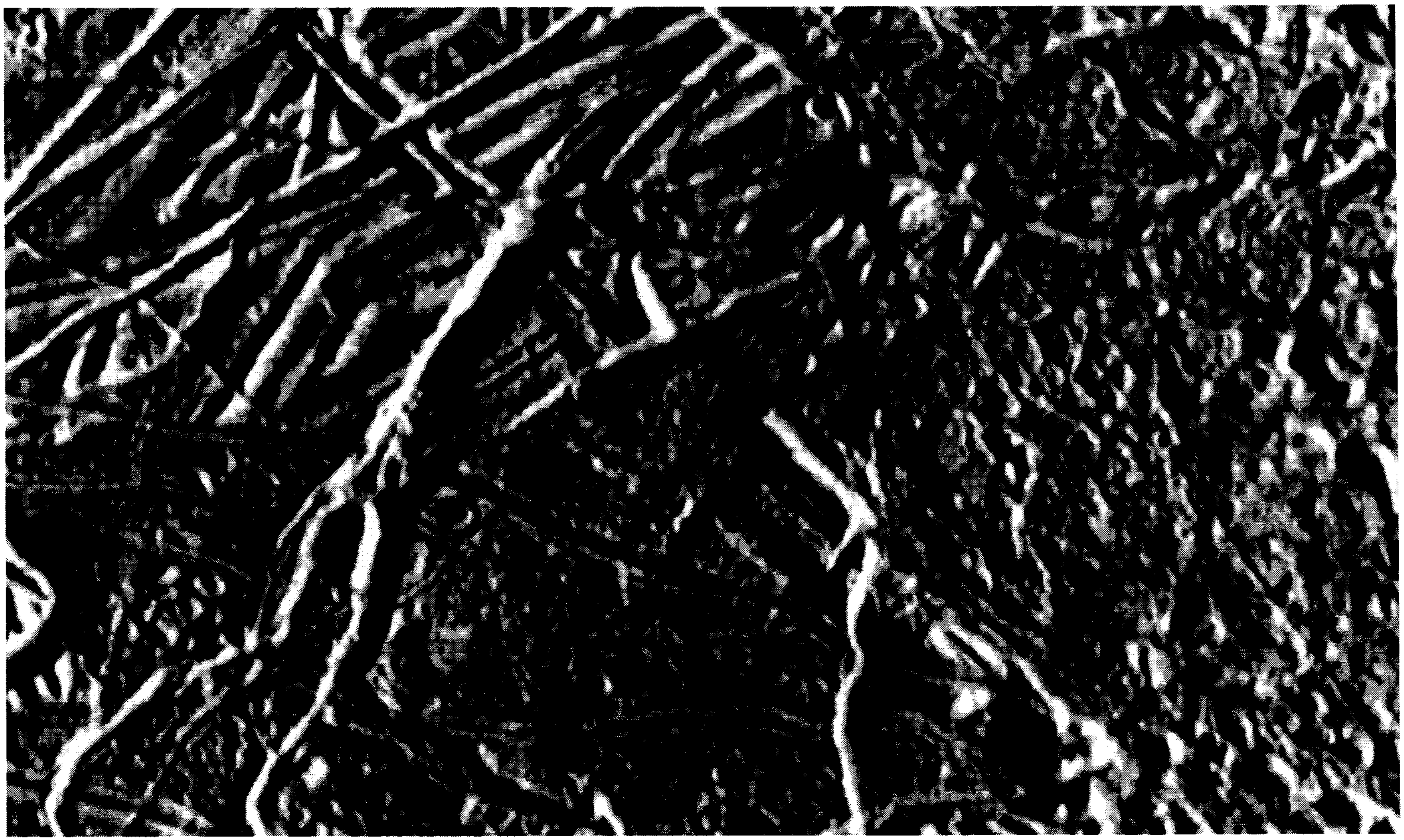
A Hypothetical Europa Crossection



Galileo Data a Wakeup Call: Especially First Europa Chaos Region



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What Is Interesting About Europa's Ocean?

It Is (Probably):

- **Old**
  As Old As Europa Itself: 4 Byrs
- **Deep--**
  Gravity Data Indicate an Ocean 75km to 200 km deep
- **Ice Covered--**
  Various Considerations Argue for Ice 5-30 km Thick
- **Saline--**
  Magnetic Data Indicate Ionic Salts
  Surface Spectra Indicate Salts Similar to Earth's Oceans
- **Unpleasant, Expensive, Challenging--**
  Hot with Radiation; Thermally Cold (70-100K); Dim;Distant; in Jupiter's Gravity Well;Pristine
- Underlain by Hydrated Salts Containing Key Planetary History Data
- **Compelling**

So, We Need Technology To Explore A Subglacial Ocean On Another Planet

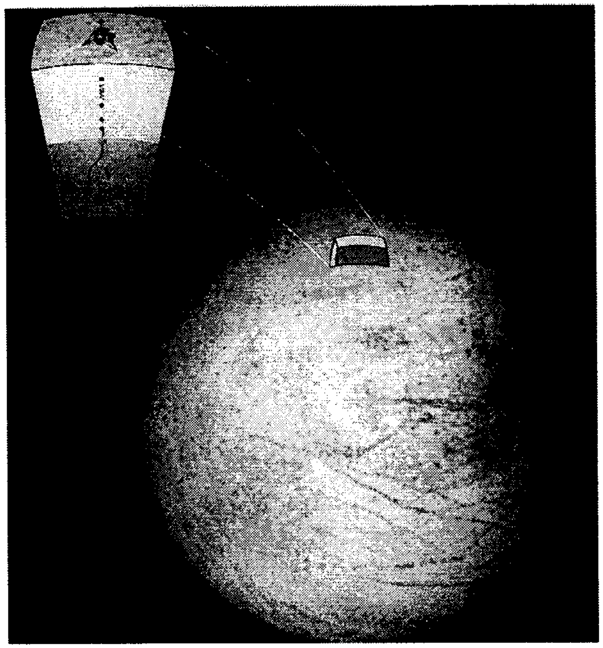
This is a List We Know How to Write:

- Vehicles for Mobility in Ice and Water
- Methods for Regional/Global Surveys (Sounding Radar)
- Power/Communications systems
- Miniature Scientific Instruments
- Planetary Protection
- Autonomy for Science and Operations

We Have Started to Address that List

Full Development is a Long-Term Process

Europa Subsurface Mission



Critical Technology

- Subsurface Access
- In situ instrumentation
- Contamination control

Other Important Technology

- Subsurface navigation
- Communications
- Power sources

- ***Science Objectives***
  - Search for evidence of life
  - Determine the physical and chemical characteristics of ice
  - Determine chemical, physical and biological properties of the ocean
- ***Mission Description***
  - Landing site: Within selected region (thin ice crust or non-deforming ice)
  - Subsurface : Descend 20-30km to the ice/water interface
  - Telecon/Navigation: In-Ice transceivers and Lander telecom
  - Cost: TBD
  - Option: Profile Study of Water, Sediments
- ***Measurement Strategy***
  - Determine composition and temperature as the probe descends through the ice
  - Image features within the ice and ocean
  - Establish ocean observatory at base of ice

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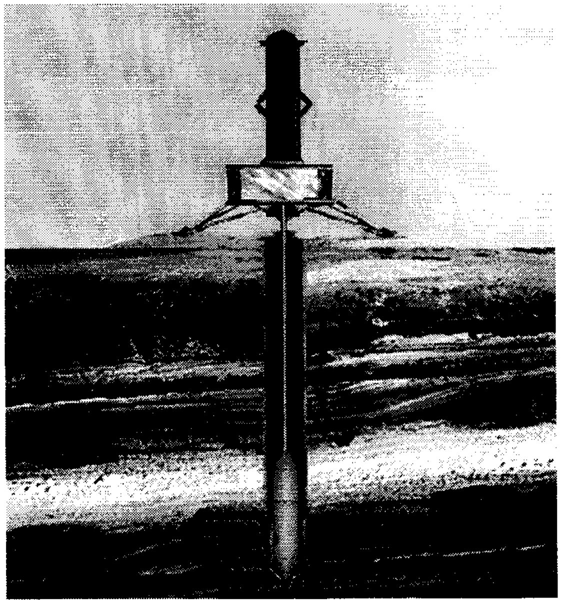
Mars Subsurface Mission



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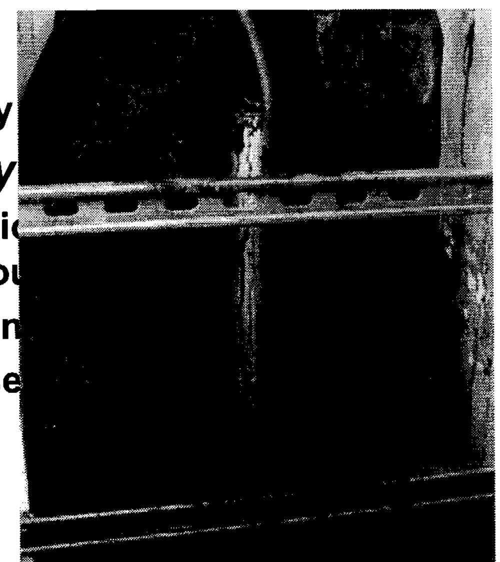
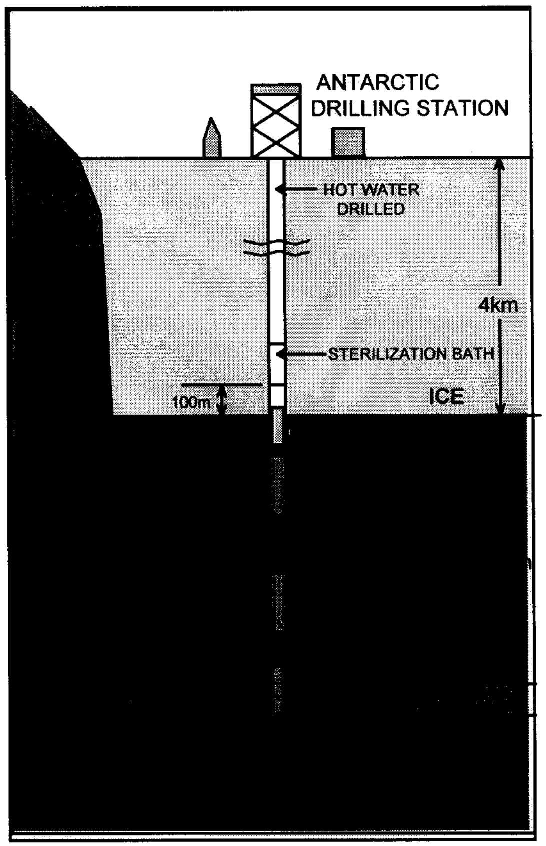
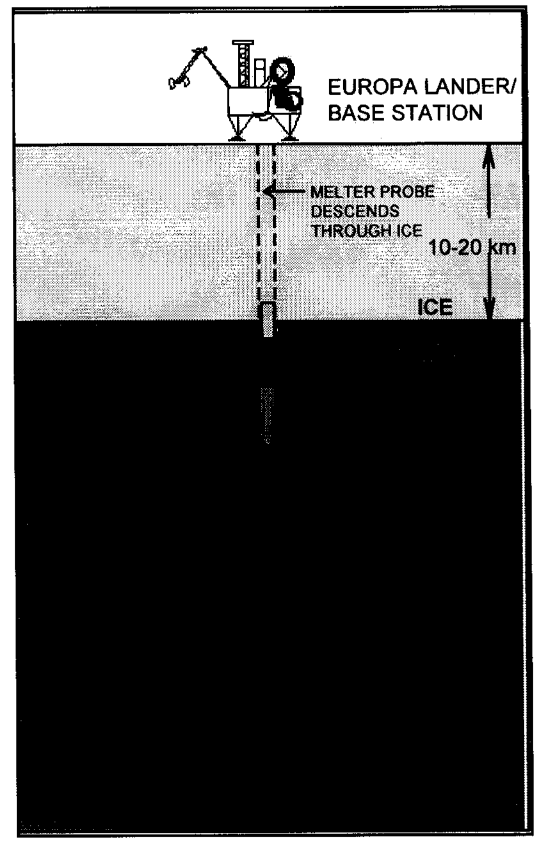


In Situ Exploration Concepts



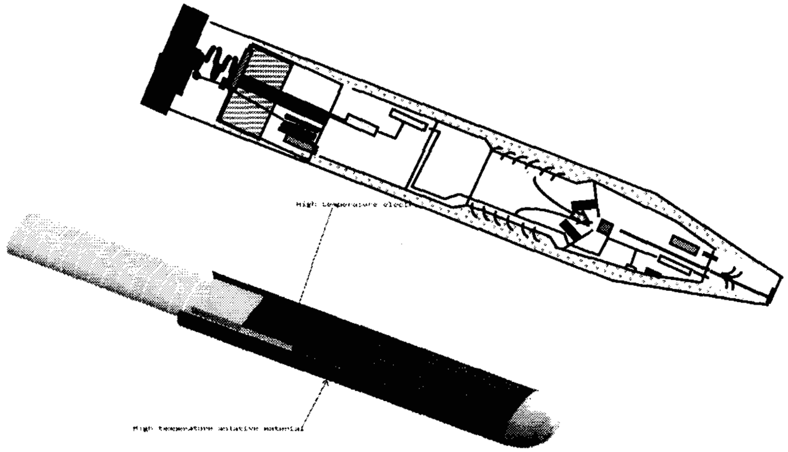
Subglacial Lake



Europa

90 km

JPL CETDP ACTIVE THERMAL PROBES FOR ICE SITES



Two Point Designs for Thermal Probes, vehicles for movement in ice

Description:
Thermal Ice Probe technology development for advanced in-situ capability and mobility.

Objectives:
FY '01: Testing mobility in ice/sediment environments
FY '02: Tethered field operation and acoustic development
FY '03: Mobility in ice/vacuum and ice transceiver development

Task Manager
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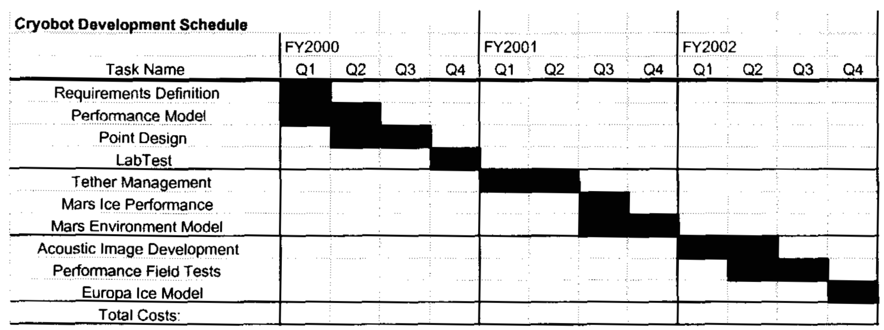
Team
JPL: Scott Anderson, Frank Carsey, Emily Eelkema, Winston Fang, Jason Feldman, Gindi French, Jeff Hall, Dan Helmik, Corey Harmon, Partha Shakkotai, Jan Tarsala, Brian Wilcox, Wayne Zimmerman
CIT: Hermann Engelhardt, Robin Bosley
ASU: Jack Farmer

FY01 Level 1 Goals:
- **Demonstrate mobility in ice/sediment mixture**
- **Tether development**



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Technology and its Relevance to Missions

The Active Thermal Probe technology has wide applicability to a variety of mission scenarios. By gaining access to the icy subsurface environment, the technology fosters in-situ science exploration. The Active Thermal Probe can take instrument suites to depth through changing stratification. Instruments can include cameras, spectrometers, and in-situ sampling instruments.

- **Icy Body Environments**
  - Comets (100m depth)
    - Subsurface Access
    - In-Situ sampling
- **Liquid Environments**
  - Europa (5-7km depth)
    - Ocean and In-Situ Exploration
  - Titan (3-5km depth)
    - Prebiotic Exploration
- **Polar Cap Environments**
  - Earth (2-4km depth)
    - Arctic and Antarctic climatic circulation
    - Antarctic geophysics and ice dynamics
    - Subglacial Lake Exploration
  - Mars (50m - 200m depth)
    - Subsurface Polar Cap Exploration
    - Climate history science
    - Exobiology science

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Comparison of Cryobot w. Historical Penetrators

Research Org	Penetrator Type	Physical Descrip	Application	Performance
Expedition Glaciology International (Philberth, 62)	Passive heater	**Length= 2.5 and 2.9m** Dia= 10.8cm **Power= 4kw** **Melt rate= 2m/hr**	Greenland ice-sheet	Depth= 218m/1km **Observations:** **- Short circuit** **- Heater burnout**
Army Cold Regions Research and Engineering Laboratory (CRREL) (Aamot, 64)	Pendulum stabl. Passive heater	**Length= 2.5m** Dia= 10cm **Power= 3-4kw**	Greenland and Antarctic ice-sheets	Depth= 6-260m **Observations:** **- Heater burnout** **- Cable fail.** **- Electronic fail.**
Univ of Nebraska (PICO) (Hansen, 84, 93, 94)	Pendulum stabl. Passive heaters in nose/shell w. ability to switch heaters on/off	**Length= 3.45m** Dia= 12.7cm **Power= 5.4kw** **Melt rate= 2-4m/hr**	Greenland ice-sheet	Depth= 120m **Observations:** **- Heater burnout** **- Coax cable fail.**
Acad of Mining and Drilling Russian Antarctic Expedition **(e.g., diesel fuel)**	Elec/mech ice corer	**Length= 2m** Dia= 8-10cm **Power= 3-5kw** **Drill rate= 1-2m/hr**	Antarctic ice-sheet	Depth~ 3km **Observations:** **- System robust** **- Contam. anti-freeze liquid rqrd** **- Signif GSE rqrd**
California Inst of Tech (Englehardt, 90-00)	Hot water drill w. water recirculated back to surface to allow reheating	**Length< 1m** Dia= 14cm **Power= 1-2Mw** **Melt rate= 3-5m/hr**	Antarctic ice-sheet	Depth~ 1km **Observations:** **- System robust** **- Large energy rqrd** **- Signif GSE rqrd**
Jet Propulsion Lab (Cryobot team, current)	**Passive/active jet Heaters in nose/ shell w. ability to switch heaters Autonomous cntrl**	**Length= 1.25m** **Dia= 12cm** **Power= 1kw** **Melt rate= .5-1m/hr**	**Antarctic ice-sheet** **Mars N. polar cap** **Europa ice-crust**	**Depth= 5m** **Observations:** **- System robust** **- Heater FET fail (post test)**

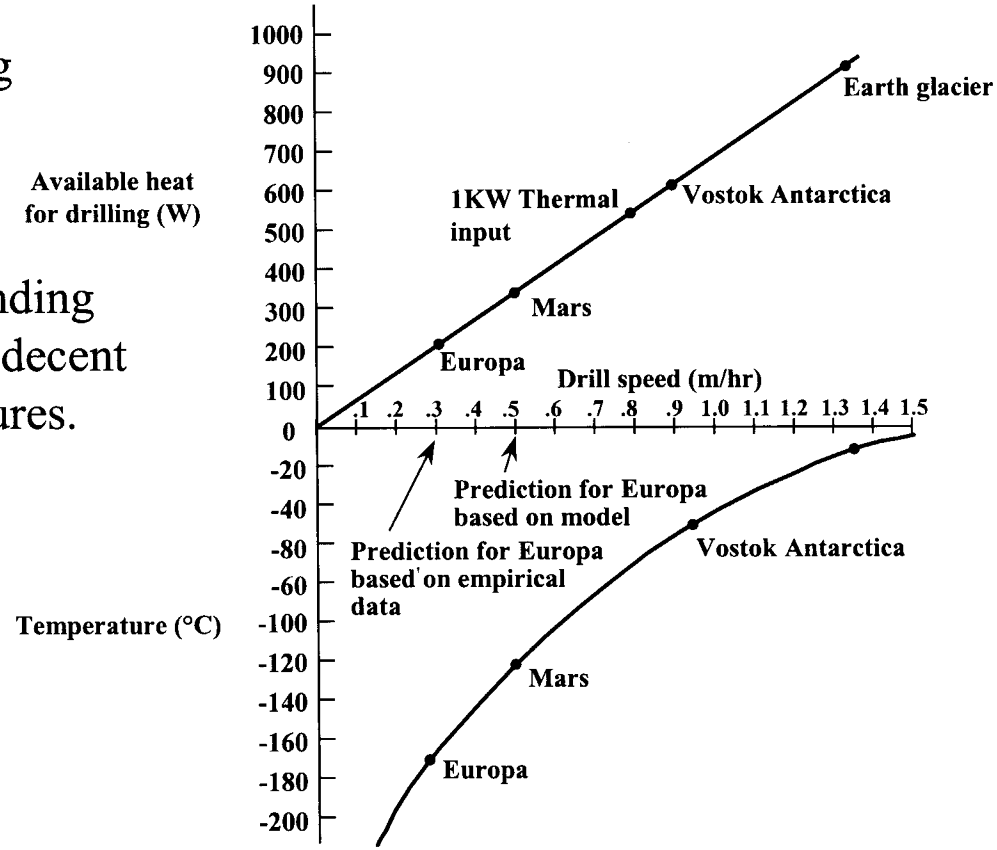
Active Thermal Probe

Technical Accomplishment:
Melting performance modeling using water jetting as a vortex drill.

Knowledge gathered helps understanding relationships between power inputs, decent rates, and ice environment temperatures.

Significance to NASA:

- Mobility through subsurface ice environments is possible.
- New access for instrumentation tools for scientific community.
- Subsurface exploration of icy planetary environments is feasible.



Drill Speed vs Heat and Temperature

Task Manager:Lloyd French

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CRYOBOT DRILLING PARAMETERS PHASE 1
(version 6 MARCH 2000)

• MELTING POWER	0.6 - 0.8 kW
• DRILLING NOZZLE DIA	1.0 - 1.25 mm
• WATER TEMPERATURE AT NOZZLE	20 - 25°C
• WATER TEMPERATURE	5 - 6°C
• RETURN WATER PRESSURE	1 - 2 bar
• WATER JET VELOCITY	10 - 20 m/s
• WATER FLOW RATE	1 - 1.5 l/min
• DRILLING SPEED	0.3 - 1.0 m/h
• DRILLING EFFICIENCY	80 - 90 %
• ICE TEMPERATURE	-10°C
• CRYOBOT OUTER DIA.	10 - 12 cm
• CRYOBOT LENGTH	1 - 2 m

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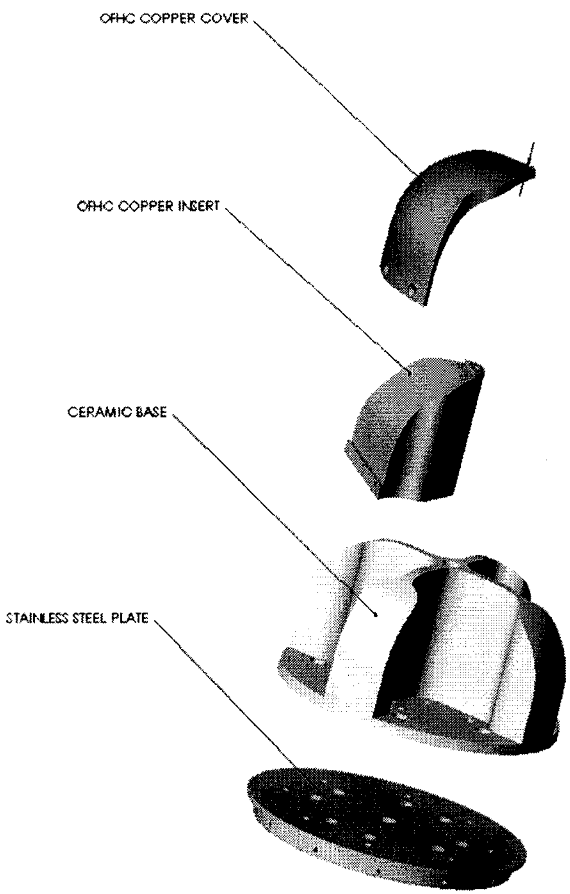
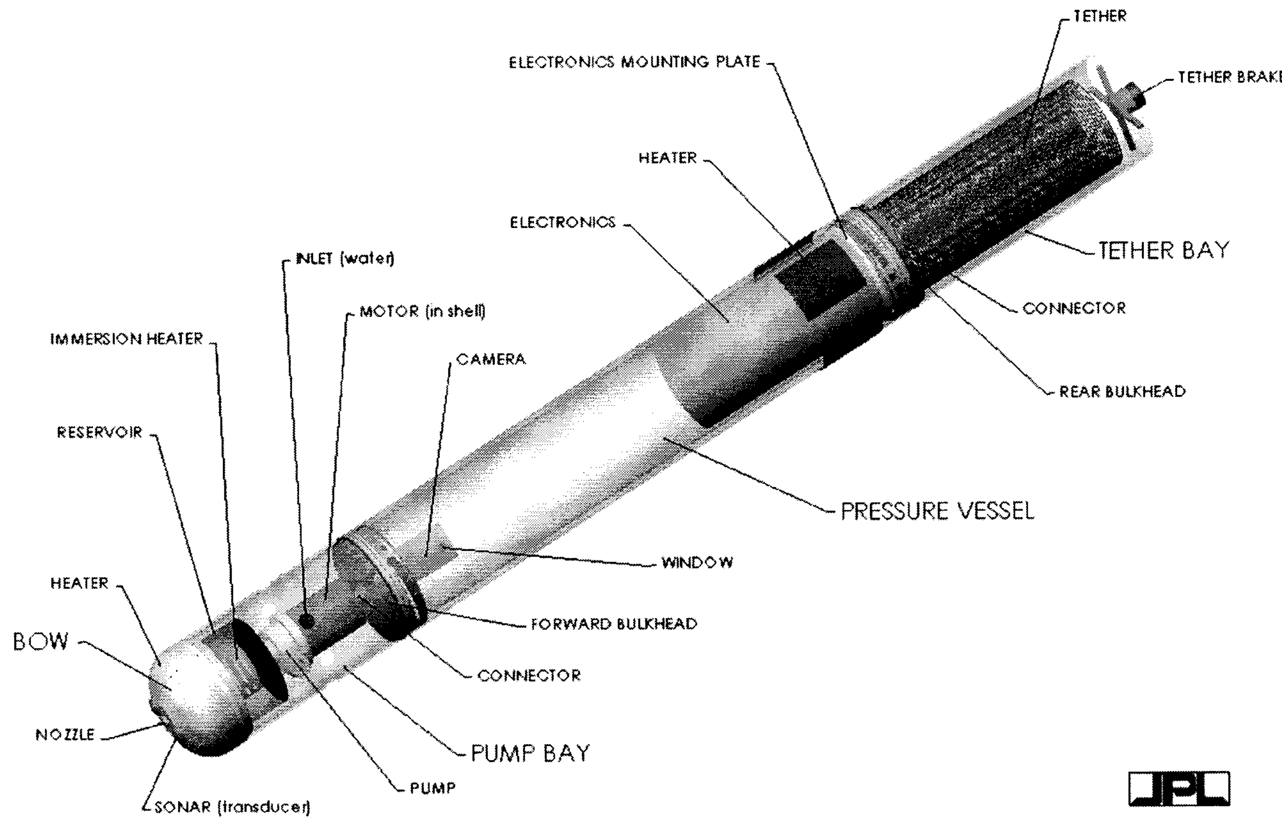
Baseline Design





Active Thermal Probe

Technical Accomplishment: The Cryobot design team completed its mid-year design review on April 25, 2000. This review provided brassboard level designs for the mechanical aspects of the probe, control electronics, instrument interfaces, and software control. Also presented were supporting empirical test results on both active and passive melting tests which clearly showed that the original models for melt rates/ efficiencies were correct. These results were essential to the sizing/selection of the electronic components, heaters, and motor/pump. The current probe design is now sized (both in terms of power and geometry) close to the proposed flight design. This is a significant achievement.

Technology: Thermal fluid modeling. High efficiency active and passive melting. Tether bundle packaging.

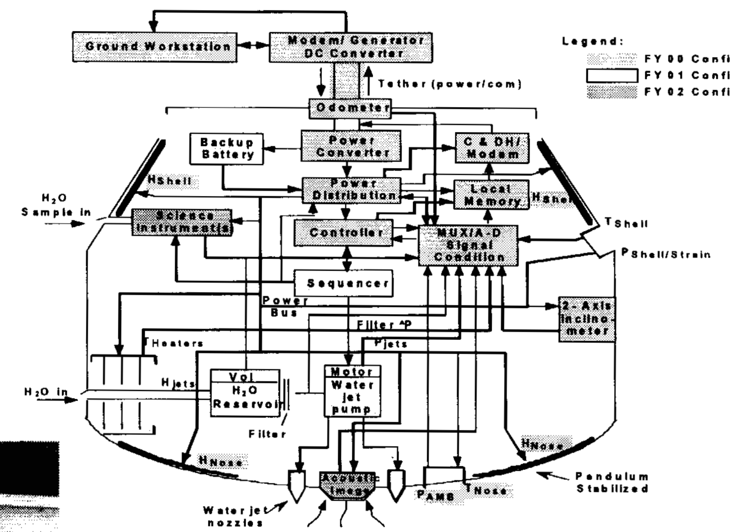
Significance to NASA:

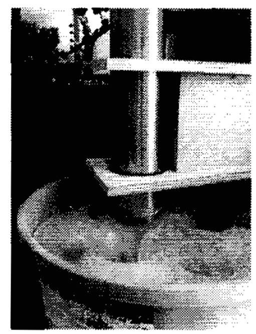
- Current empirical tests clearly show that it is possible to achieve .5 m/hr melt rates in cold ice with 1Kw thermal--this equates exactly to projected energy requirements for a similar cryobot application to Mars Polar regions or Europa;

- The current Cryobot prototype design will use off-the- shelf commercial electronic/mechanical components--this design strongly suggests that it is feasible to meet science/ functionality/control requirements while maintaining a flight-like configuration (~1m in length, 12cm dia);

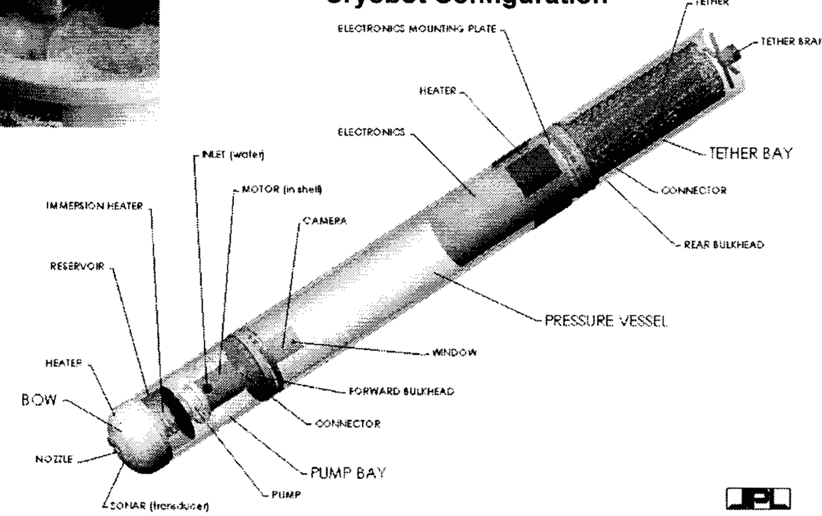
Task Manager: Lloyd French

Cryobot Functional Control Block Diagram





Cryobot Configuration



Active/Passive Tests

Active Thermal Probe

Technical Accomplishment:
Mobility through 5m of ice. Utilizing Active/Passive melting systems. Added demonstrated capability of steering during descent.

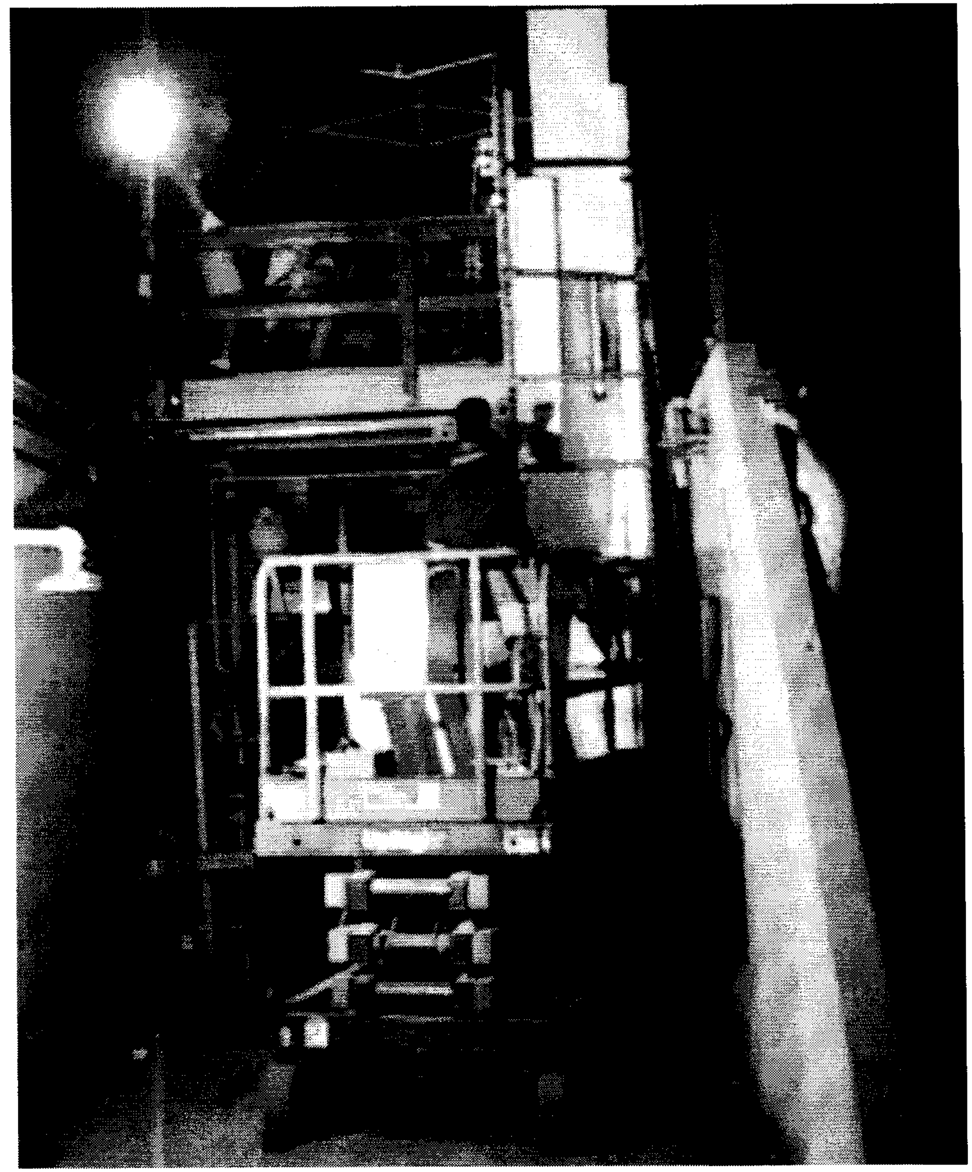
Total time:	11.3 hrs
Ave Power:	417.7 W
Ave Descent Rate:	43.4 cm/hr

Significance to NASA:

•Mobility through subsurface ice environments is possible.

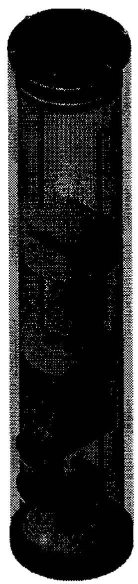
•New access for instrumentation tools for scientific community.

•Subsurface exploration of icy planetary environments is feasible.



Task Manager: Lloyd French

ICE BOREHOLE CAMERA DEVELOPMENT AND DEPLOYMENT (NASA CODE Y PROJECT)



Critical Technology

- Strategy Assessment
- In situ optical instrumentation

Other Important Technology

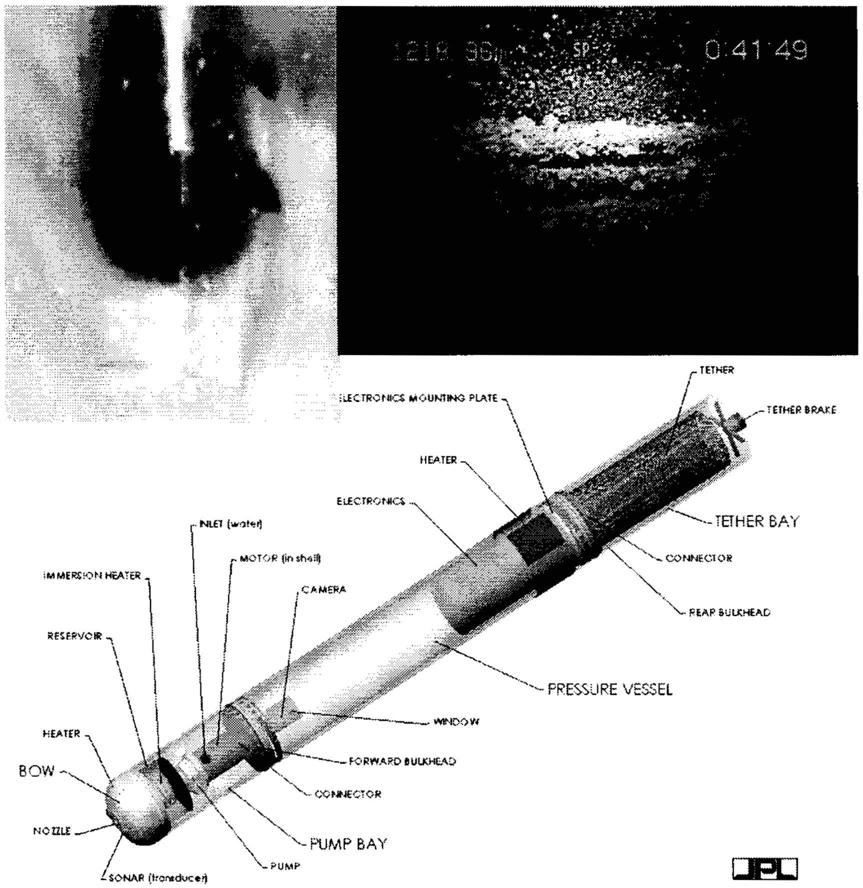
- Data Handling
- Contamination control

Extended cryobot capabilities

- (Sample return, coring, etc)

- ***Science Objectives***
  - Profile physical, chemical and isotopic properties of ice and inclusions
  - Characterize biology of Ice and Bed
- ***Mission Description***
  - List and evaluate science objectives and requirements
  - Develop and test instruments
  - Develop field project concepts
  - Cost: TBD per year
- ***Measurement Strategy***
  - Determine composition and isotopic abundance within ice/ocean environment
  - Optical investigations of subsurface features
  - Evaluate new micro-instrumentation
  - Assess sample return: water, ice, sediments

Benefits



Cryobot

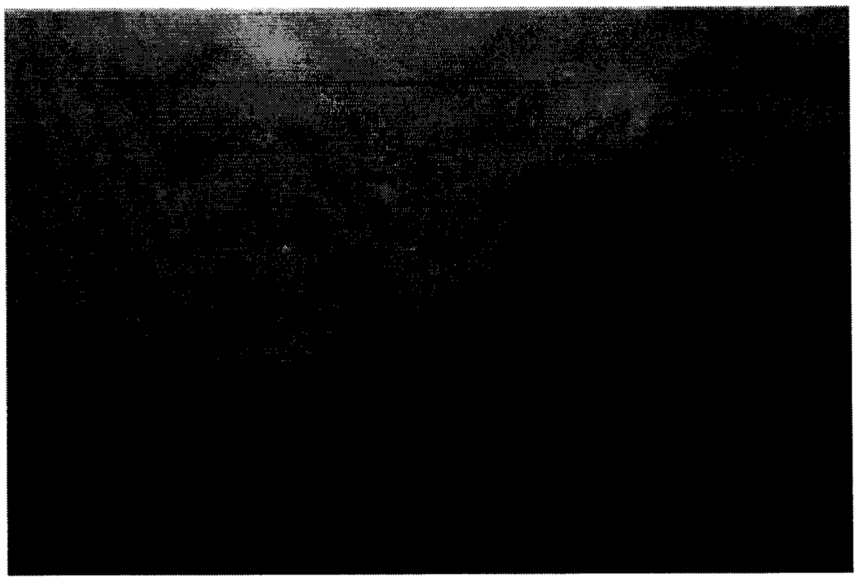
Technology Focus

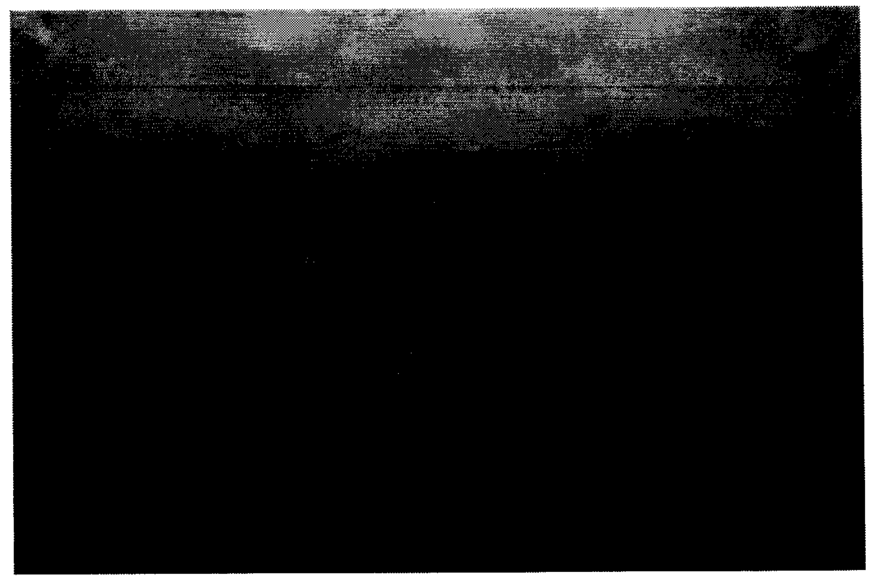
The Active Thermal Probe is a unique robotic system that **represents a major breakthrough** in subsurface mobility:

- **Access** to the icy subsurface environments will be possible;
- **Science instruments** including microscopic cameras, spectrometers, and in-situ sampling for ice chemistry **will reveal M's yrs of climate history and possible life forms**

- Deep ice penetration:
  - Access to Europa's Ocean
  - Access to Mars Polar Caps
- Access to pristine protected subsurface icy environments (Earth, Mars, Europa)
- Subsurface icy environments best for
  - Exobiology, Astrobiology (life detection)
  - Climate history and volitiles
  - Geochemistry, Geophysics, Geology

ICE BOREHOLE CAMERA IMAGES, ICE STREAM C, WEST ANTARCTICA, 2000-2001 SEASON
DEPTH 951 M





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Major Milestones for FY 01 and Beyond

- FY 01: Mobility in ice/sediment and tether development
- FY 02: Tethered field operation and acoustic development
- FY 03: Mobility in ice/vacuum and ice transceiver development
- FY 04: Consequences of Contamination control
- FY 05: Subglacial lake field operation
- FY 06: Subsurface sample return development